THE CLIMATIC FACTOR

AS ILLUSTRATED IN ARID AMERICA

BY

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NOTE TO THE READER.

This volume as a whole deals with climate, but various parts are concerned with particular aspects of the problem. The reader who is interested in one special phase is referred to the following chapters:

Physical aspects of the Southwest, Chapters I to VI.
The Ancient People of the Southwest, Chapters VII to X.
The Measurement of Rainfall by the Growth of Trees, Chapters XI to XIV.
The Maya Civilization and Changes of Climate in the Torrid Zone, Chapters XV to XVIII.
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The volume may be divided in another way according to the sciences with which the different chapters are more especially concerned. In this division, however, it must be recognized that there is much overlapping, for the same chapter often deals with several sciences.

Climatology, Chapters I, XIV, XVI, XIX.
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The reader who desires to understand the main outline of the theories here presented, but does not care to go through all the details of evidence is advised to read the Introduction, and Chapters VI, VII, IX, XIII, XIV, XVI, XVII, XIX, and XX.

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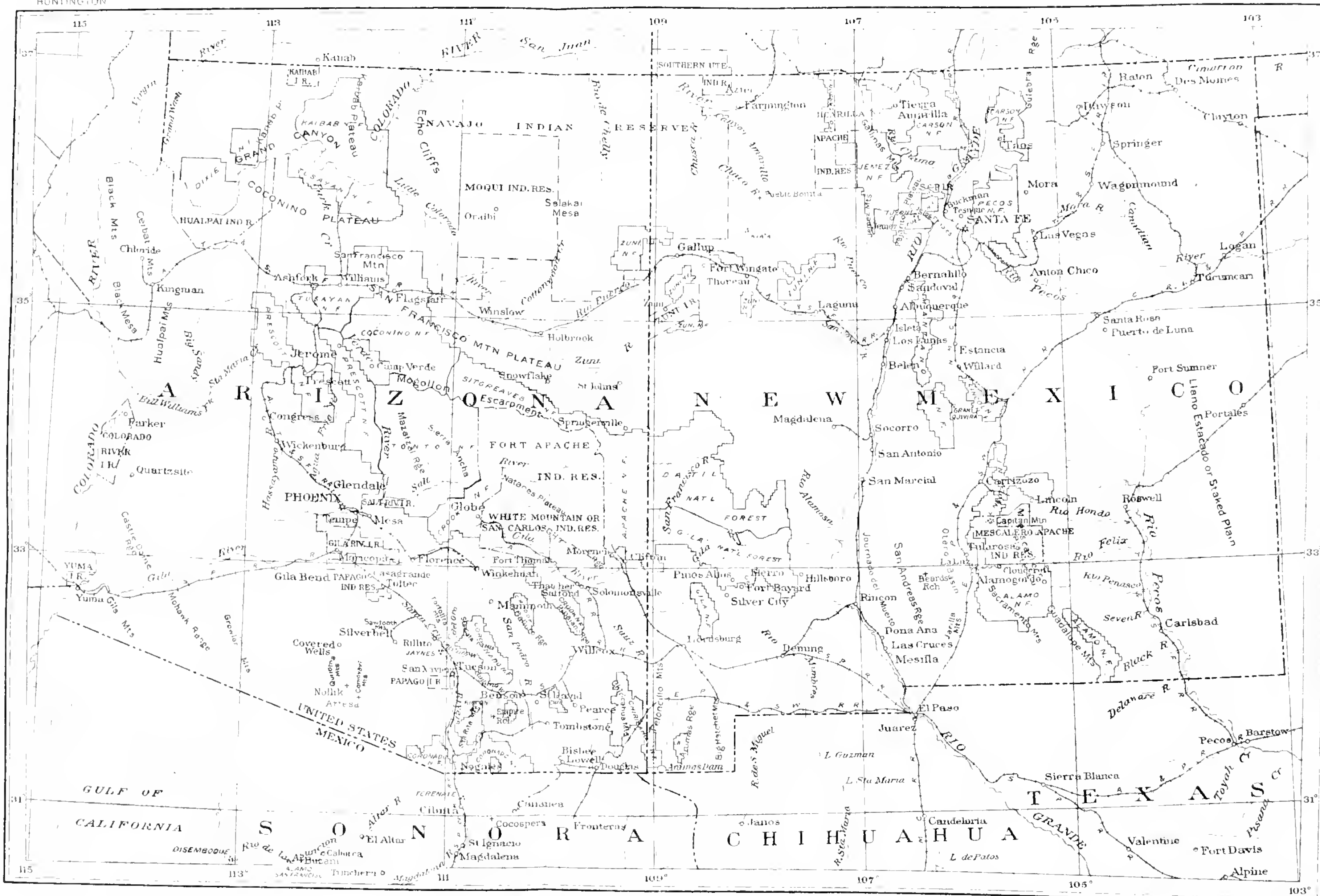

SKETCH MAP OF ARIZONA AND NEW MEXICO
SHOWING LOCATION OF PLACES MENTIONED IN THE TEXT

100 50 0 100 Miles

INTRODUCTION.

Climate as an element of physical environment is so well recognized that there is no need to demonstrate its importance. By common consent it is held to be a primary factor not only in the life of plants, animals, and man as they exist to-day, but in their entire evolution. Moreover, among the main elements of physical environment it alone is subject to pronounced changes in comparatively brief periods. The form of the lands, the location of mountains, and the composition of the atmosphere are doubtless all subject to great changes, but these are too slow to have much effect upon a single generation of living beings or even upon all the generations that have existed during the period since man emerged from barbarism. Small climatic changes, however, such as those from one year to the next, or from one decade to another, are constantly in progress, and their far-reaching results are a matter of every-day experience. Moreover, it is quite possible that larger changes have taken place during the past 2,000 or 3,000 years, and if this is the case their effects must have been correspondingly important. The investigation of this possibility is the purpose of this volume.

The study of changes of climate naturally divides itself into two parts, relating to the present and to the past. The facts as to the present are being rapidly gathered by the excellent work of the various National Weather Bureaus of the world. The facts as to the remote past are being studied minutely by geologists so far as they relate to geological times. Comparatively little, however, is known as to the state of affairs during the period covered by history and man's later development. Yet a knowledge of this period is essential. In the first place, it is only by accurate knowledge of past variations that we may hope to ascertain the causes of present variations, and thus to predict those which will occur in the future. Geological evidence of course tells us much about the past, but it pertains largely to periods too remote to be of great present importance, and its phenomena can not be dated with accuracy in terms of years. Hence something else is needed to fill the gap between such geological phenomena as the glacial period and our modern climatic records covering scarcely a century. In the second place, a mathematical investigation of the chief effects of present climatic conditions may do much to show how far human habits, customs, physiological traits, and mental character are influenced by physical environment, but it is impossible to determine the exact effect of present conditions until we know how long those conditions have lasted and how the environment of the past, especially during the last 2,000 or 3,000 years, differed from that of the present. Hence along many lines the study of the climatic variations of historic times is essential as the foundation of future work.

The present volume is an attempt to determine the sequence and character of such variations on the basis of evidence in the drier portions of America from Guatemala on the south to Idaho on the north. A large number of phenomena from the diverse fields of geology, archeology, history, and botany seem to agree in indicating that during the past 3,000 years North America has been subject to pronounced climatic pulsations similar to those which appear to have taken place in Asia and other parts of the Old World. In the temperate portions of the Eastern Hemisphere the climate of the past appears on the whole to have been distinctly moister than that of the present. The change from the past to the present, however, does not seem to have been gradual and regular, but pulsatory or cyclic, so that certain periods have been exceptionally dry, while others have been wet. In America the same appears to be true.

The facts set forth in this volume are the result of investigations carried on in coöperation with the Department of Botanical Research of the Carnegie Institution of Washington, at the invitation of the Director, Doctor D. T. MacDougal. The first field season, March, April, and May, 1910, was devoted to the study of a relatively restricted area centering at Tucson, the site of the Desert Botanical Laboratory in southern Arizona, and extending southwestward for 150 miles to the shores of the Gulf of California in northwestern Mexico. During the second season the months of March and April, 1911, were devoted to the investigation of selected sites in various parts of New Mexico, while May and June were occupied with measurements of the rate of growth of about 200 Sequoia trees in the central parts of the Sierra Nevada Mountains in California. The third season was divided into two portions. In the first place, six weeks during March and April, 1912, were spent among the lakes and ancient ruins of southern Mexico and Yucatan. In the second place, the work upon the Sequoias in California was carried further, and about 250 more trees were measured. Finally, in March and April, 1913, independently of the Carnegie Institution, the author made a journey to Guatemala for the purpose of investigating the ruins of that region and their relation to the physical surroundings and vegetation of the country.

Throughout the work much attention was given to the influence of the present climatic conditions upon physiography and upon the habits and distribution of plants and animals, including man. No attempt will be made to deal with these subjects here, however, except in so far as they bear upon changes of climate. The purpose of this volume is primarily to investigate the extent and nature of such changes and our attention will be devoted almost exclusively to that subject, while the interesting problems of the relation of climate to human character and history will be left for another volume. The first portion of our investigations will be concerned entirely with New Mexico, Arizona, and the adjacent parts of the Mexican state of Sonora. Inasmuch as an intelligent knowledge of present climatic conditions is essential to a full understanding of the past, the present climate of those regions and its relation to the great climatic zones of the earth as a whole will form our first subject of consideration. A minute knowledge of the land forms of the region is not necessary for our present purpose, but a clear conception of the main types and of their relation to climatic conditions is advisable. Accordingly a chapter will be devoted to the general aspect of New Mexico, Arizona, and Sonora, and to the chief types of physiographic forms commonly found there. To complete the picture a brief chapter on vegetation will be added, not from the point of view of the botanist but of the geographer.

Having gained a general idea of the physical aspects of New Mexico and Arizona, we shall be prepared to turn to some of the details which furnish evidence as to past climatic conditions. First we shall take up those lines of inquiry which involve only physical processes without respect to man. Among these a foremost place is occupied by the alluvial terraces which are so widely distributed throughout all arid mountainous regions. Their importance as possible indicators of climatic changes is so great that I shall consider the problem of their formation in detail. The strands of ancient lakes are often closely associated with river terraces, and the conclusions to be drawn from them are similar. Our region has so few lakes and these few have been so little investigated that they are of less importance than many other lines of evidence. Nevertheless, the Otero soda lake near Alamogordo in New Mexico and the group of small lakes near the City of Mexico are of such interest as to warrant a somewhat full discussion. The desiccated bed of the Otero Lake presents evidences of a changing climate not only in its old strands, but in the remarkable series of gypsum dunes of various ages which surround it; while in the Mexican lakes natural causes appear to have induced variations in size even during the period since the coming of the Spaniards.

From the purely physiographic portion of our investigations in Arizona, New Mexico, and old Mexico, we shall proceed to the main phase of the subject—the study of traces of ancient human occupation. In this part of the work we shall examine a large number of ruins scattered from the shore of the Gulf of California to the northern limits of New Mexico, 500 miles away. Except among a few archeologists, the number of ruins is rarely appreciated. The ruins not only indicate a considerable degree of culture, but they show distinctly that different races occupied the same sites in succession. The successive occupations were separated by periods of abandonment, due possibly to climatic causes, or perhaps to something quite different, but at least well worthy of study. In considering the ancient ruins and their prehistoric inhabitants it is essential to keep fairly in mind two opposing theories. The first, which is usually accepted, holds that the large number of ruins does not indicate a correspondingly large population, and that the physical conditions of the country in the past, just as at present, forbade any great number of inhabitants. The other, which is accepted by only a few scholars, holds that the ruins were occupied by a relatively dense population which persisted for a long time. This could have been possible only on the assumption of greater rainfall than now, and therefore those who hold this view believe in changes of climate.

The lines of reasoning followed thus far are similar to those which I have employed in respect to various countries of Asia, and which were first set forth in a volume entitled "Exploration in Turkestan," published by the Carnegie Institution of Washington in 1905, and have been amplified and revised in "The Pulse of Asia" and "Palestine and its Transformation," published in 1907 and 1911, respectively. The conclusions derived from these lines of reasoning are open to the criticism that a preconceived theory may have led to the interpretation of phenomena according to that theory. Hence, before the conclusions here indicated deserve final acceptance, it is necessary to compare them with the results obtained by the observations of other unprejudiced workers, or with the independent results of some new method in which the personal equation plays no part. Fortunately the work of Professor A. E. Douglass, of the University of Arizona, suggests a method by which old trees may be used as a mathematical measuring-rod in order to determine exactly what climatic events have occurred during the last 2,000 or 3,000 years. Accordingly, considerable space will be devoted to setting forth the results of the measurement of the rate of growth of nearly 500 Sequoia trees among the Sierra Mountains in California. A large number of other measurements of trees by the United States Forest Service have been kindly put at the disposal of the Carnegie Institution of Washington by the Forester, Mr. Henry S. Graves, and a discussion of them is included in this volume. By purely mathematical methods, unaffected by any personal bias, it has been possible to obtain curves indicating the climatic pulsations of the last 3,000 years. A comparison of these curves with the results obtained from other lines of evidence, both in America and Asia, shows that in spite of certain disagreements the general climatic history of both continents appears to have been characterized by similar pulsations having a periodicity of hundreds or thousands of years.

If the conclusions outlined above are accepted, they may perhaps furnish a key to the pre-Columbian chronology of America. Apparently the Southwest has been first relatively inhabitable and then relatively uninhabitable during periods lasting hundreds of years. The dates of these periods are ascertainable from ancient trees. Each propitious period has probably been a time of expanding culture and comparatively dense population, while the unpropitious periods have been times of invasion, disaster, and depopulation. Archeological study has begun to differentiate periods of this sort, but has been unable to date or correlate them. If the evidence of climate be considered together with that of archeology, we may perhaps at length be able to overcome the absence of written documents so far as to construct a fairly intelligible record of the history of our ancient predecessors.

The broader the area under observation, the greater is the probability of accurate results. Hence, after two field seasons in Arizona, New Mexico, and Sonora, it seemed wise to extend the work more than 1,300 miles southward to southern Mexico and Yucatan, and finally 400 miles farther into Guatemala and Honduras. Here again the lines of reasoning previously employed in Asia and later in the United States and northern Mexico gave similar results. In Yucatan and Guatemala, however, a new type of phenomena was also found, which confirmed the previous conclusions most interestingly. In that tropical region the presence of magnificent ruins in the midst of dense forests seems to indicate changes of climate contrary to those of the regions farther north. On the whole the country appears to be moister than it was several thousand years ago, instead of drier, as in regions farther north. This at first sight appears contradictory, but in reality it confirms a conclusion derived from other evidence, namely, that changes of climate are probably characterized by the shifting of the world's great climatic zones from north to south, and the reverse.

Having reached this conclusion, we find ourselves able to test it by means of another of wholly independent nature based on a comparison of historic events and climatic changes in Europe and Asia. This second conclusion is that while the course of history depends upon a vast number of factors and its details are due to what may be designated as purely human causes, yet in its broader outlines it is profoundly affected by climatic changes. These may alter economic conditions, they may disturb the adaptation of a race to its environment by fostering special diseases, or they may force people to move out of a habitat where they can no longer compete with nature. In Yucatan and the neighboring parts of Central America the dense tropical forests and their deadly malarial fevers are man's chief enemy. Our study of the terraces, ruins, trees, and other phenomena of the United States and northern Mexico leads to the hypothesis that the forests of Yucatan and the surrounding regions have alternately increased and diminished in size, the increase coming at times when aridity prevailed in regions such as California, and the decrease during California's moist times. Our hypothesis as to the relation of changes of climate and history leads to the inference that civilization in Central America would thrive when the forests diminished and would decline when they increased. A comparison of the climatic periods indicated by the Sequoias with the events of the history of the ancient Mayas of Yucatan, as recorded on monuments and in chronicles, shows that our expectations are realized to a considerable degree. Thus both conclusions are strengthened.

The degree of certainty given to our conclusions by the agreement of the evidence of old trees with that derived from other sources brings us to the point where we may reasonably attempt to ascertain the cause of changes of climate. In such an attempt the first matter to claim attention is a certain degree of coincidence between the phenomena of climate and those of the sun. There are many reasons for thinking that the well-known sun-spot cycle of 11 years is related to a distinct climatic cycle. The longer, but less thoroughly established 35-year cycle of Brückner also appears to be correlated with the activity of the sun. These things, as has often been pointed out, suggest that our minor climatic fluctuations may be due to slight variations in the intensity of the sun's radiation. The work of Langley, Abbott, and others proves that the sun's radiation actually does vary, while that of Köppen, Newcomb, and many more proves that the temperature of the earth's atmosphere shows a corresponding variation. The terrestrial variation is so slight, however, and is so irregular outside of equatorial regions, that some of the best authorities doubt whether it is sufficient to produce appreciable results. Opposed to this is the fact that by almost universal consent students of glaciation believe that a permanent lowering of the earth's mean temperature to the extent of from 3° to 10° C. would produce a glacial period. The most conservative estimates of the change in terrestrial temperature between the minimum and maximum of sun-spots is about 0.5° C. This is so large a fraction of the change needed to produce glaciation that it seems as if it must produce some appreciable meteorological results.

It is true that attempts to detect such results have hitherto proved contradictory, but this is not surprising. It seems to be due partly to the lack of long, homogeneous records and partly to failure to make due allowance for the different degrees to which different kinds of phenomena, such as temperature, pressure, wind, and rain, must lag behind their cause, especially under conditions such as those of the atmosphere, where large quantities of heat are transferred from one region to another. The new method of investigation of climate by means of the growth of trees, as elaborated by Professor Douglass in his contribution to this volume, furnishes long, homogeneous records, and these show a distinct sun-spot cycle. The careful researches of Arctowski upon "pleions" and "anti-pleions" seem not only to demonstrate a relation between solar phenomena and terrestrial climate, but also to show why the manifestation of this relationship is irregular and, at first sight, contradictory. These things lead to the conclusion that the small climatic cycles now in progress upon the earth are in large measure due to variations in the sun.

In regard to greater climatic changes, it appears that the pulsations of the past 3,000 years are too large to be due to fortuitous rearrangements of the earth's atmosphere because of purely terrestrial causes. On the other hand, they occur too rapidly to be due to precession of the equinoxes, changes in the carbonic-acid content of the air, or deformation of the earth's crust. Hence we are led to conclude that they, too, are due to variations in the sun. The same conclusion seems to apply to glacial and interglacial epochs, since their characteristics appear to be identical in nature with those of the pulsations of historic times, although differing greatly in degree. In explanation of still greater changes, however, such as the radical difference between the distribution of climatic zones in the Permian and Pleistocene eras, something else is demanded. In Part II of this volume the matter is fully presented by Professor Schuchert from the standpoint of the paleontological geologist. We are there led to the conclusion that while changes in the amount of carbonic-acid gas in the atmosphere may explain certain climatic phenomena, they can not explain this particular feature. Crustal deformation, on the contrary, seems fully adequate to cause just such a redistribution of zones as we find from time to time in geologic history. It apparently can not, however, account for the climatic instability which often accompanies or immediately follows periods of crustal deformation, that is, for fluctuations from glacial to interglacial conditions and for minor pulsations. In explanation of these it seems reasonable to turn back to our solar hypothesis. Thus we are led to the final hypothesis that for some unknown cause both the earth and the sun have been repeatedly thrown into activity at approximately the same time. The activity of the earth seems to manifest itself in the changes of form whereby continents are uplifted and mountain ranges shoved up. That of the sun seemingly displays itself in pulsations which give rise to climatic variations of every grade, beginning with glacial and interglacial epochs and ending with little cycles like that of the sun-spots.

Here we leave the matter, but not without a word of caution. Throughout this volume our purpose is not to develop the hypothesis just outlined as to the interrelation of solar activity, crustal deformation, and climatic changes. That hypothesis, important as it may prove, is by its very nature open to grave question. At best it is merely a corollary of our main conclusion, whose truth or falsity is in no way dependent upon it. The primary purpose of this book is to investigate any possible climatic changes which may have taken place in historic times. Our main conclusion is that such changes have taken place and that they have been of a pulsatory nature. All other questions are here subordinate, and the truth or falsity of this conclusion is the point upon which attention should be focused.

PART I.

THE PROBLEM OF RECENT CLIMATIC CHANGES.

CHAPTER I.

THE MONSOON CLIMATE OF ARIZONA AND NEW MEXICO.

The climate of Arizona, New Mexico, and northern Sonora is of a peculiar, transitional type. It may be defined as a subtropical continental climate of the monsoon variety. It resembles that of the provinces of the Punjab, Rajputana, and Sind in northern India more closely than that of any other part of the world. As the region extends from about north latitude 28° in Mexico to 37° in northern New Mexico and Arizona, its subtropical position brings most of it within the great world-zone where high pressure and consequent aridity normally prevail. Here the main movement of the air is downward and outward; and here the northeasterly winds of the trade-wind zone and the southwesterly winds of the zone of prevailing westerlies find their origin.

If the climatic zones of the earth were not interfered with by the different rates at which land and sea are heated and cooled, seasonal changes would bring this region within the range of the prevailing westerlies and their rain-bringing cyclonic storms in winter, and within the trade-wind belt in summer. In winter the country would receive a fair amount of rain for a few months, the edges, so to speak, of the great storms which whirl across more northerly regions not only in winter but in summer. During the rest of the year it would be rainless, for in spring and fall it would be in the subtropical zone of high pressure and descending air, while in summer the trades would blow across it from the northeast. Inasmuch as the trades would come from a dry interior, they would bring no rain. As a matter of fact, however, the trade-winds are never well developed in Arizona and New Mexico, and herein lies the explanation of the most peculiar characteristics of the climate. The cyclonic storms of the westerlies in winter and the descending air of the subtropical "horse latitudes" in spring and autumn give rise respectively to the rain and the aridity which would be expected. In summer, however, because of the great size of the continent of North America, the trade winds which would be expected do not appear; their place is taken by relatively moist winds which blow in general from the south, and may be called monsoons for lack of any more appropriate name.

In order to give definiteness to our discussion of the climate of the southwest, let us recall the familiar general principles of the effect of continents upon temperature, pressure, winds, and rainfall. Land masses, as is well known, become heated or cooled much more quickly than expanses of water. Hence, in winter the continents become much colder than the oceans, and are therefore the seat of centers of high barometric pressure, a condition exactly the reverse of that prevalent over the comparatively warm oceans. From the continental areas of high pressure the winds tend to blow outward, especially toward the east and south. Thus the cold waves of the Eastern and Southern States arise, for on the western side of ordinary cyclonic storms the indraft of air occasioned by the storms themselves is strengthened by the general high pressure prevailing in the cold interior of the continent. Inasmuch as Arizona and New Mexico, unlike the parts of India with which we have compared them, are not protected by an east-and-west range of mountains such as the Himalayas, chill winds from the north sweep over the country in winter, producing frequent frosts. Even as far south as Tucson, in latitude 32° and at an elevation of only 2,300 feet above sea level, the thermometer occasionally falls to 16° F. Except in the warmest and lowest places, such as the Gila Valley around Phoenix, or at Yuma on the Colorado River, this liability to sudden cold prevents the growth of subtropical fruits, such as oranges, although much farther north in California these grow to perfection. Oddly enough, the warmth of the winter in the intervals between cyclonic storms, when north winds do not prevail, is almost as fatal to such northern fruits as apricots and peaches as is the low temperature to oranges. Since this is a desert region of clear skies and slight humidity, the daily extremes of temperature are naturally great, amounting often to 40°. In February, or even January, it is not uncommon for the mercury to rise to 70° F., and if the nights are above the freezing-point the fruit trees are stimulated to open their blossoms too early. A blighting wind from the north swoops down, and the flowers are nipped.

In summer the conditions are the reverse of those of winter, except that the range of temperature from day to night is still extreme. The whole continental interior becomes greatly heated and in Tucson the temperature rises occasionally to 114° F., and at Yuma still higher. Under such circumstances low barometric pressure must of necessity prevail, and winds from the periphery of the continent tend to blow inward. This tendency is so

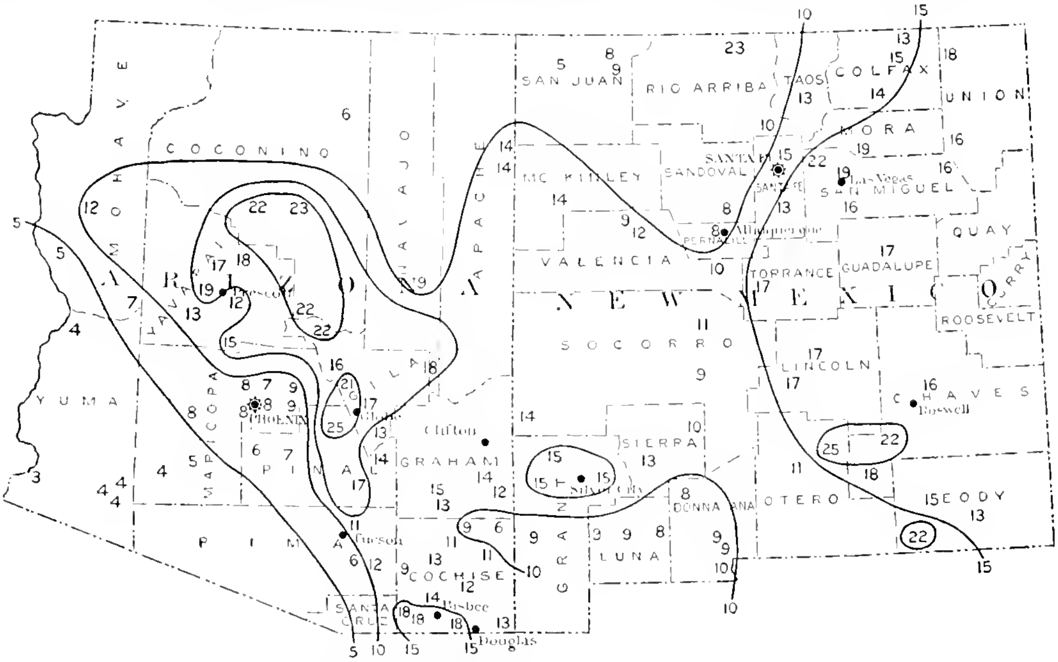

Fig. 1.—Rainfall of Arizona and New Mexico. The figures show annual rainfall in inches.

From two maps published in Bull. No.188, Bureau of Plant Industry, U. S. Dept. Agriculture.

strong that toward the end of June the trade winds, which would normally be expected in the district from Arizona southward, are entirely destroyed. They prevail in normal fashion over the adjacent oceans, but on the continent they give place to somewhat irregular winds whose prevailing direction is distinctly northward. They form, as it were, an inward draft blowing from the Gulf of California and the Pacific Ocean on the one hand, and from the Gulf of Mexico on the other, toward the continental center of low pressure. In all essential respects they are like the monsoons of India, although less strong and distinct because of the smaller size of the continent. As the American monsoons approach the land, the first tendency is for them to become heated and hence relatively dry, for the land is hotter than the ocean, and in many places the height of the mountains is too slight to overcome the heating due to the land. The case is like that of the plains of Sind at the mouth of the Indus. As the winds blow inward, however, they are soon forced to rise by the mountains, they reach more northerly and hence cooler latitudes, and they enter the continental area of low pressure where the general tendency of atmospheric movements is upward. Thus in the peninsula of Lower California, in the Mexican states of Sonora and Chihuahua, and in Arizona and New Mexico, the summer is characterized by heavy thunder-showers of the kind commonly known as tropical. These usually occur from about the end of June to the early part of September, beginning earlier and ending later in the south than in the north. Thus the country has two rainy seasons, one in winter deriving its rain from cyclonic westerly storms, and one in the summer deriving rain from southerly monsoon thunder-storms.

The total rainfall is small, ranging from 5 to 20 inches per year in most parts of the area, as is shown in the map, figure 1, and rising above 20 inches only in the high mountains. The variation from year to year, however, is great, as may be seen in figure 2, where the rainfall of Tucson is plotted by calendar years. The rainfall of the two seasons, summer and winter, is still more variable, a fact evident from figure 3. The average of the winter season at Tucson is 4.5 inches. The amount is small because the moisture comes largely from the Pacific and must cross the high Sierras on the way. The winds, of course, often blow from the east at the actual time of rainfall, but this affords no indication of the source of the moisture. In all cyclonic storms of the northern hemisphere the motion of the air around and toward the centers of low pressure is similar, and the southeastern quadrant of a cyclonic area lying in front of the storm where the air has not yet suffered depletion of its moisture, and where the winds move rapidly from warmer to cooler latitudes, is apt to have a rainfall more abundant than that of any other quadrant. Much of the rain which accompanies such winds has doubtless come from the oceans to the eastward, but more has probably been brought by the prevailing westerly winds and is merely caught up and prepared for precipitation by the easterly winds.

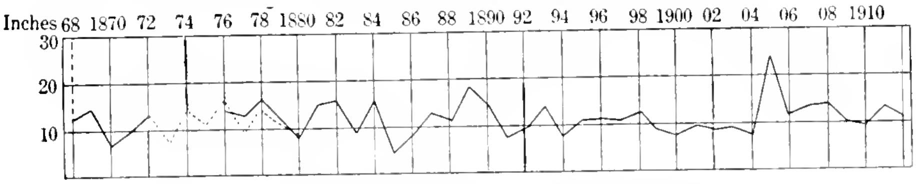

Fig. 2.—Annual Rainfall at Tucson, Arizona, 1868–1912.

The paucity of the winter rainfall would not be so harmful were it not for its extreme variability. In the winter of 1903–4 the total precipitation at Tucson for the six months from November to April, inclusive, amounted to only 1.08 inches, while in the succeeding year it amounted to 14.74. Records kept at Tucson and at the neighboring army post of Fort Lowell show that in the years from 1868 to 1912 the winter rainfall was less than 2.5 inches, or practically useless, in 9 winters; it amounted to from 2.5 to 5 inches, that is, it was fair, in 20 winters; it ranged from 5 to 7.5 inches, or was good, in 13 winters, and exceeded 7.5 inches only three times. (See table 1*a*.) These figures do not show quite the true state of affairs so far as agriculture is concerned, for 3 inches in February and March, after the chief frosts are over, are worth double that quantity in November and December. Still, the figures serve to give an idea of the extreme variability and uncertainty of the winter rains. Manifestly, even with the help of irrigation, the prospects of the farmer are not of the rosiest when he may have only one-fourteenth as much rain in one year as in another.

After the dry spring season — the fore-summer, as MacDougal has called it*— the southerly monsoon gradually becomes well established by the strong indraft toward the heated continent, and thunder-showers finally begin upon the mountains. Far to the south in Mexico the first showers may come in May or even April. In southern Arizona they usually begin, as we have seen, toward the end of June or early in July, while farther north

* D. T. MacDougal: Botanical Features of North American Deserts. Carn. Inst. Wash. Pub. 99, 1908.

they do not come till mid-July. In exceptionally warm years, however, they may begin unusually early because of the more rapid heating of the continent. Thus in 1910 the mean temperature of the month of May at Tucson was 6° F. above the average of the preceding four years; and showers, light on the plains, but heavy on the mountains, began early in June. Farther north, where the showers begin later, they also end earlier, and instead of lasting into September, terminate in August. Everywhere they are accompanied by vivid lightning and the rainfall is torrential.

The summer rains are more abundant and less variable than those of the winter. At Tucson they average 7.14 inches for the six months from May to October inclusive. During the 45 years embraced in the records at Tucson and Fort Lowell the minimum was 3.01 inches in 1885 and 3.03 in 1900, while the maximum was 14.2 inches in 1876. Fifteen summers had a rainfall of less than 5 inches, 12 from 5 to 7.5 inches, 9 from 7.5 to 10 inches, and 9 over 10 inches. The summer showers are so sudden and the rain falls so rapidly that a large part of the water runs off in great floods, serving no useful purpose. Nevertheless, the showers support considerable vegetation, and from the earliest times have enabled the inhabitants to cultivate quickly growing crops like corn and beans, but neither these nor any other crops can be grown without irrigation except in a few places at great altitudes; yet in these places there is always danger of failure. Even with the aid of irrigation the arable area is at best extremely limited. The division of the rainfall into two seasons has, as we shall see, a beneficial effect upon native vegetation, but it can scarcely be considered particularly advantageous to agriculture, especially to the type brought by the inhabitants of Europe to the better-watered parts of the United States.

Table 1a.—*Summer and Winter Rainfall at Tucson (and Fort Lowell) from 1868 to 1912.*

[See Figures 3 and 4].

Summer of—	Inches of rainfall.	Winter of—	Inches of rainfall.
1868	8.19	1867– 68	4.43
1869	9.48	1868– 69	4.10
1870	4.86	1869– 70	2.25
1871	7.12	1870– 71	2.10
1872	11.48	1871– 72	1.27
1873	3.43	1872– 73	3.09
1874	7.90	1873– 74	7.31
1875	8.90	1874– 75	2.97
1876	14 20	1875– 76	2.20
1877	6.37	1876– 77	4 21
1878	11.16	1877– 78	6.42
1879	4.29	1878– 79	5.80
1880	4.88	1879– 80	5.07
1881	12.64	1880– 81	2.66
1882	10.27	1881– 82	4.35
1883	4.57	1882– 83	4 08
1884	4.47	1883– 84	6.53
1885	3.01	1884– 85	5.88
1886	4.27	1885– 86	4.32
1887	10.69	1886– 87	2.08
1888	4.25	1887– 88	3.34
1889	11.50	1888– 89	8.98
1890	10.66	1889– 90	5.14
1891	3.93	1890– 91	5.75
1892	4.05	1891– 92	5.56
1893	9.95	1892– 93	2.50
1894	3.12	1893– 94	3.24
1895	6.14	1894– 95	2.26
1896	9.33	1895– 96	5.38
1897	8.66	1896– 97	3 06
1898	7.46	1897– 98	3.32
1899	5.66	1898– 99	4.64
1900	3 03	1899–1900	2.87
1901	7.43	1900– 01	5.66
1902	4.14	1901– 02	1 06
1903	5.80	1902– 03	6.23
1904	6.12	1903– 04	1.08
1905	5.85	1904– 05	14.74
1906	4.78	1905– 06	7.17
1907	10.88	1906– 07	7.77
1908	7.92	1907– 08	4.01
1909	7.19	1908– 09	4.13
1910	7.22	1909– 10	2.88
1911	7.58	1910– 11	4.42
1912	6 68	1911– 12	3.76

From a theoretical standpoint the rainfall of Arizona and New Mexico is peculiarly interesting because the winter rains possess the characteristics of the temperate zone and the summer rains those of equatorial regions. It is not possible to enter into any detailed discussion of the subject at this time, but one or two matters may be pointed out as especially deserving of study. In the first place, at high elevations among the mountains the seasonal distribution of precipitation is not the same as in the lowlands. For instance, on the Santa Catalina Mountains, over 9,000 feet in elevation, Dr. MacDougal has found not only that the rainfall is two or three times as large as down below, as might be expected, but also that the winter rains are heavier than those of summer. This, of course, is the reverse of what prevails in the lowlands. It seems to mean that the climate of the mountains approximates to that of regions farther north, not only in temperature, but in the character of its storms. In other words, it seems as if westerly winds and their attendant conditions prevailed for a longer time, or else during the same time, but more completely at high levels than at low, while in the districts of lower altitude equatorial conditions are predominant so far as precipitation is concerned. To put the matter in another way, it may be that the heating up of the continent in summer disturbs the equilibrium in the upper air so much less than in the lower that the rainfall at high altitudes is influenced much less than at low. As yet, data obtained on the subject are not sufficient to permit of any trustworthy conclusions. The matter is mentioned here merely as one of the many interesting problems which would repay investigation.

Another problem of the same kind is illustrated in figures 2 and 3. The curve of figure 2 represents the total rainfall by years from 1868 to 1912 as given in the Summary of the Climatological Data for the United States and in the Monthly Weather Review. Figure 3 shows the summer rainfall for the six months from May to October inclusive and the winter rainfall for the six months from November to April during the same term of years. The latter two curves seem to indicate a reciprocal relation of some sort between the rainfall of summer and winter. In general, when the summer rains increase in amount the winter rains decrease, and vice versa. This phenomenon is not confined to Tucson, but is apparently characteristic of the Southwest as a whole. For instance, in the two curves at the lower left-hand corner of figure 11, on page 109, it is clearly seen in the rainfall of Flagstaff, 200 miles north of Tucson and 5,000 feet higher. Inasmuch as a similar relation between the rainfall of equatorial and temperate regions has been inferred from

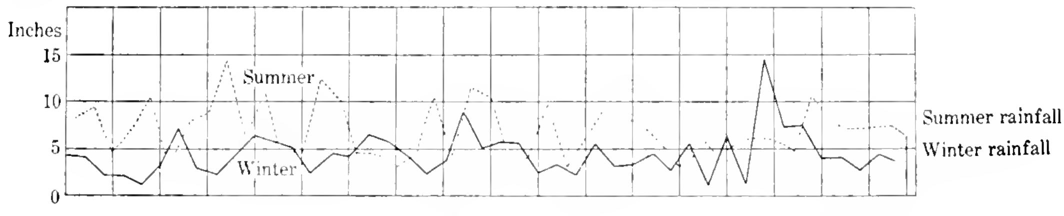

FIG. 3.—Winter and Summer Rainfall at Tucson, Arizona, 1868–1912.

—— = Winter rainfall, Nov.-Apr. —— = Summer rainfall, May-Oct.

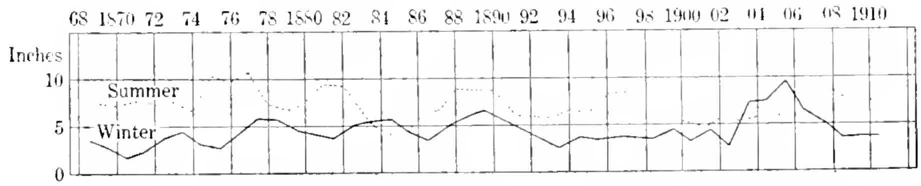

FIG. 4.—Comparison of 3-year Means of Winter and Summer Rainfall at Tucson, Arizona, 1868–1912.

the comparison of records in various parts of the world, particularly India, it is of great interest to find it so clearly manifest here. Examination of the curves shows that in two cases out of every three a minimum of winter rain is followed by a maximum during the succeeding summer. One would expect to find the reverse also true, and that a summer maximum would be followed by a winter minimum, but this does not hold good. A summer minimum, however, is usually followed by a winter maximum. In other words, if it be permissible to generalize on so small a basis of fact, the minima appear to be the critical points. A maximum, either in summer or winter, is not likely to be followed by especially marked conditions in the succeeding season. A minimum, on the contrary, whether in summer or winter, is likely to be followed immediately by a maximum in the succeeding season.

The preceding generalization obviously holds good only about two-thirds of the time. In figure 4 the summer and winter curves have been smoothed by using 3-year means instead of the actually observed rainfall. When the minor fluctuations are thus eliminated, the opposed phases of the summer and winter curves are brought out clearly in the period from 1868 to 1887, and less clearly from 1895 to 1907. In the period from 1888 to 1894 the diagram presents a wholly different appearance: the two curves show agreement instead of opposition. The effect of such agreement upon the economic life of the country is marked. During the late eighties, when both summer and winter rains were on the increase, the cattle industry flourished as at no other period. In the early nineties, however, when the rain of both seasons decreased, dire distress prevailed. Cattle died by the thousand and the industry received such a blow that on many ranches there are now only hundreds of animals where then there were thousands. The peculiar fashion in which the summer and winter curves show opposite phases part of the time, and then suddenly agree, suggests various speculations as to the cause. It looks as if there might be more than one type of cyclical or periodic variation in the activity of the earth's atmosphere. One type perhaps causes agreement and one type disagreement. Here, as in the case of the contrast between the precipitation of high and low regions, it is too early to attempt to form positive theories.

CHAPTER II.

THE TOPOGRAPHIC INFLUENCE OF ARIDITY.

In the modern science of physiography as developed in recent years, under the leadership of Professor Davis, one of the most interesting features is the connection between the form of the earth's surface and the climate of any given region. Not only do glaciated areas possess their own peculiar topography, but so do humid and dry regions. The scenery of Arizona and New Mexico is stamped indelibly with the impress of an aridity which has lasted hundreds of thousands of years. Just when it began we can not tell, but certainly far back in the Tertiary era, and possibly earlier, for deposits characteristic of aridity not only attain a great thickness superficially, but are interbedded with marine strata in formations dating far back in geological time. A full discussion of the effects of aridity upon the form of the land in all parts of New Mexico and Arizona would require a volume and would demand an amount of field work far greater than I have been able to give to the matter. Accordingly, in the following pages I shall limit myself to a few salient features which clearly show evidences of aridity, or are of special importance in relation to changes of climate and the ancient human occupation of the country.

Topographically Arizona and New Mexico consist of two chief parts, plateaus of nearly horizontal strata 5,000 to 7,000 feet high and basin regions where mountain ranges, due to faulting or to rapid uplift of relatively small areas, alternate with more or less completely inclosed basins filled with alluvial waste. In Arizona the plateaus and the basin ranges are sharply separated by the Mogollon Escarpment, a line of southward-facing cliffs which extend approximately northwest and southeast across nearly the whole State and pass almost through its center. North of the escarpment lies a high plateau broken in places by fault scarps running north and south, diversified by extinct volcanoes and cut by deep canyons, like that of the Colorado, but preserving almost uniformly the practically level position of its rock formations in spite of thousands of feet of uplift since their original deposition. South of the escarpment the basin-range region lies at a general elevation 3,000 or 4,000 feet less than that of the plateaus. Here the strata by no means lie horizontal, but have been tipped this way and that, chiefly by means of block faulting along lines running more or less closely north and south. The spaces intervening between the uplifted blocks form basins which have been filled with alluvium. Thus to the eye of the traveler the difference between the plateaus and the plains may be briefly summed up by saying that the plateaus are a region of great plains cut by deep canyons, while the basin-range country is composed of great plains broken by narrow mountain ranges. In New Mexico the separation between the plateaus and the basin ranges is not so distinct as in Arizona. In the elevated regions of the northwest, however, and in the Staked Plains of the eastern part of the State the plateau quality is as well marked as in Arizona, while basins and ranges of mountains due to faulting are almost as characteristic a feature in the south as in the neighboring State to the west. In the center, especially toward the north near Colorado, the main chain of the Rocky Mountains extends down into New Mexico and adds a distinct type of topography. The mountains, however, soon break up into isolated ranges rising from the plateau or bordering waste-filled basins, so that most of the country may fairly be said to belong to one of the two main types with which we are dealing. Inasmuch as the main chain of the Rockies has little to do either with the early inhabitants or with the other evidences of climatic changes with which we are here concerned, it will not be further discussed.

THE TOPOGRAPHIC FEATURES OF THE PLATEAUS.

(1) *Mature Uplands.*—Where most typically developed the plateaus present three chief types of topographic form, which may be described as mature uplands of ancient origin, young plains of erosion upon soft strata, and young cliffs composed of hard strata and forming the borders either of mesas or canyons. Other features, such as volcanic cones or fault scarps, for example, may be omitted as of secondary importance in spite of their great interest. The plateaus, it is needless to say, were formed by the slow uplifting of large areas of the earth's surface without any pronounced tilting or bending of the rocks. In all such cases an old topography, brought to a greater or less degree of maturity, must have been carried up to a height far above that under which it was originally developed. In some cases—for example, the Kaibab Plateau in northern Arizona just north of the part of the Grand Canyon most commonly visited—this ancient topography is still preserved. On the edges it is being rapidly dissected and removed by the rapid streams which are the normal result of uplift. The Mescalero Plateau, east of the Otero Basin in the south central part of New Mexico, is another good example. Here a steep fault scarp, gashed by precipitous young canyons, rises on the east side of the basin to a height of about 9,000 feet, nearly 5,000 feet above the basin floor. At the top one emerges from the narrow valleys formed since the last uplift and finds himself in a wooded region of open, mature topography. Gentle slopes rise from broad valleys to round-topped hills of nearly uniform height. Everywhere the soil is deep, and outcrops of naked rock are rare. Often the valleys converge into flat sink-holes, where the water stands for a while before it can seep away through underground passages in the soluble limestone. Everything indicates that the region was subjected to extensive erosion long before it was slowly upheaved to its present situation. Its topography was formed under conditions quite different from those of to-day, and we can as yet draw no satisfactory conclusion as to the climate prevalent during the long ages required for its erosion.

(2) *Young Plains due to Erosion.*—The mature uplands are in most cases so elevated as to be too cold for extensive habitation or agriculture. On their borders, however, the processes of erosion have in many cases given rise to broad and relatively youthful plains of subaerial denudation at altitudes of 6,000 or 7,000 feet. These would be habitable if provided with more water, and many of them seem to have been cultivated in former times. The plains are rarely smooth for any great distance. At frequent intervals they are interrupted by steep-sided mesas, lines of cliffs, or canyons, the product of the same process of erosion which has produced the plains. It is unnecessary here to enter into any detailed description of this well-known process. I would merely call attention to the fact that it reaches a high state of development only in arid regions. Where strata of unequal hardness are exposed to erosion, such soft materials as shales are worn back much faster than hard formations, such as massive sandstones or limestones. If the strata are horizontal the weathering of the soft formation tends to carry it away from under the hard formation wherever a vertical surface is exposed by erosion. The hard rocks of course break off as soon as they are undermined, and thus steep cliffs are formed. This process takes place in a moist climate quite as much as in a dry, but it can not go so far. In the moist climate two things tend to check it. In the first place, the action of frost, rain, snow, and vegetation tends to cause the weathering of the hard rocks to go on at a rate which approximates that of the soft rocks more nearly than in dry regions. Hence relatively more talus falls from the cliffs of moist regions than from those of dry regions, and the tops of the cliffs are worn back, while the soft strata at the base are protected by the accumulation of débris. Hence steep cliffs are not common. In the second place, erosion is less hindered in dry regions than in wet. The torrential character of the rains and the absence of vegetation allow the talus to be carried rapidly away in arid countries, while the barren-

ness and dryness of the surface allow the wind to etch out the soft rocks in a fashion quite unknown in moist lands. Consequently, where strong contrasts of hardness exist in a dry climate the soft rocks may be worn back for miles, leaving the underlying hard rocks to form broad plains of erosion, while the remnants of the overlying hard rocks form mesas. Where the climate is moist the sharp contrast between the hard rocks and the soft is diminished, as we have seen. Moreover, the number of residual hills of hard rock is likely to be large because of the abundance of streams and consequent minute dissection. Thus the plains of erosion are apt to be more broken by hills than in dry regions, while the slopes are gentler because more masked by talus.

(3) *Cliffs bordering Mesas and Canyons.*—The origin of the steep cliffs of the plateau country is evident from what has just been said. The uplifting of the plateaus has caused rapid erosion and the swift deepening of valleys. The differences between hard and soft strata have resulted in a benched topography; the hard layers form cliffs while the soft wear back so as to form benches on top of the hard. Where the cliffs wear back far from the streams, leaving plains, the hard formations may still retain their steepness, and thus mesas and buttes arise. For our present purpose this is important, partly because such topography is characteristic of arid regions, and still more because of its relation to human occupation. The ancient cliff-dwellers, who figure so largely in American archeology, made most of their dwellings in narrow canyons just at the point where the lowest soft layer makes a hollow under the overlying hard layer. Starting, probably, with no shelter except that of the cliffs overhanging their wind-scoured caves, they gradually learned to dig caves in soft formations such as the volcanic tuff of the Pajarito Plateau near Sante Fe in northern New Mexico, while later they developed the art of building walls in front of the caves, and these in turn led them to build entire rooms, sometimes three or four rows deep, at the base of the cliffs. Others among the ancient Americans utilized these same cliffs for protection, building their houses of stone on the tops of great steep-sided mesas, of which the Mesa Verde is the best known. Many of the ancient inhabitants, as may be seen near the remarkable ruins of the Chaco Canyon in northwestern New Mexico, dwelt at the base of the cliffs, but apparently cultivated the plains of erosion high above their heads. This last matter is still in dispute, but there can be no question that the peculiar topography characteristic of arid plateaus was the warp upon which was woven one of the most interesting of all the phases of pre-Columbian American civilization.

THE BASIN REGIONS.

(1) *The Mountain Slopes.*—Going down from the plateaus to the basin regions of the south, we find a country where, during the most ancient times, men dwelt as numerously as in the plateaus, although the remaining ruins are less conspicuous. Here, as there, three chief elements of physiographic form dominate the landscape: (1) rough, rocky mountain slopes, usually of steep ascent; (2) gently sloping piedmont deposits of gravel merging imperceptibly into smooth plains and playas of fine silt; and (3) terraces composed of alluvium, chiefly in the form of gravel. For convenience I shall not attempt a general description of these elements, but shall describe them as they occur in the region of Tucson, where much of our future investigation will center. This will serve as well as a more general description, for in all essential matters there is little difference between the various parts of the basin region.

Near Tucson the mountain slopes, the first of our three physiographic elements, form the sides of irregular ranges scattered here and there like islands in the midst of a sea of gravel and silt. In general the mountains run northwest and southeast. They vary in height from 4,000 to 9,000 feet, while the plains lie at an altitude of 2,000 to 3,000 feet, diminishing to the west and increasing to the east in New Mexico. Some ranges, such as the Santa Catalinas northeast of Tucson, the Tortolitas farther to the north, and the Sierritas to the southwest, are of disordered structure and consist of masses of granites and gneisses flanked by sedimentary rocks of Paleozoic or later age. The majority of the ranges, however, are composed of Paleozoic sedimentary or metamorphic rocks, together with later lavas. Most are fault blocks which have been uplifted on the southwest side of lines of faulting running northwest and southeast, and have been tilted in such a way that the back of the block slopes toward the southeast. The structure is not regular, for there has been a large amount of secondary faulting. As none of the faulting is recent, the mountains are maturely dissected. This does not mean that sharp forms of peak and cliff are rare. On the contrary, many of the fault-block ranges are carved into the most striking forms, and all the mountains display a great amount of naked rock. The little Tucson Range, for instance, which lies just to the west of Tucson, and is composed largely of andesite and other eruptives, presents one of the most jagged sky-lines to be found anywhere in America, a striking sight against the clear sunset sky. The Sawtooth Mountains, a few miles to the west, are of the same structure, and are, if anything, still more jagged. The granitic mountains, on the other hand, are not characterized by prominent peaks. From a distance they present the appearance of great solid masses, but near at hand are seen to be full of splendid deep canyons, often with precipitous walls of naked rock.

The rockiness of the mountains speaks strongly of arid climatic conditions. Mountains in a similar stage of dissection in a moist climate would be covered with soil and would present graded slopes for the most part. In Arizona the slopes are largely washed bare of soil because lack of moisture restricts the growth of plants and prevents the accumulation of roots and fallen leaves which would hold the soil in place when heavy showers tend to wash it down. The truth of this statement is apparent from the fact that the low mountains, under 5,000 feet or so in height, are more rocky and on the whole more rugged than those which rise higher. The high mountains, such as the Catalinas, which, as we have seen, rise to a height of 9,000 feet, enjoy a much greater rainfall than the lower portions of the country, at least twice as much apparently. They are also cooler, so that evaporation is far less active than in the hot regions of lower elevation. Accordingly the supply of moisture available for plants is far in excess of that below, and the mountains above 5,000 feet are covered with forests. At the lower levels oaks and bushy trees of the smooth-barked manzanita and its allies prevail, while, higher up, the mountains are densely clothed with splendid forests of juniper and pine. In the mountains of moist lands the amount of soil commonly decreases from the bottom upward. In southern Arizona the case is different; from the base of the hills, at an elevation of approximately 3,000 feet, the amount of soil decreases in the normal fashion at first, but after 1,000 or 2,000 feet it begins to increase, and at a height of 6,000 or 7,000 it is much greater than at the base. Such conditions can occur only in an arid climate among mountains rising high enough to receive a considerable rainfall.

(2) *The Bahadas, or Piedmont Gravel Deposits.*—The second element in the landscape in the basin region is the vast accumulation of gravel, sand, and silt which flanks the mountains on every side. This accumulation of detrital material slopes gently away, mile after mile, becoming flatter and flatter, until many of the slopes merge into level playas. The name "bajada" has been applied to such slopes by Tollman.* The Spaniards use the word "bajada" to designate any sort of descent, including the process of descending, but in the absence of any other appropriate term in English, I feel constrained to adopt it. The word is pronounced "bahadtha," the sound of the *d* being neither *d* nor *th* exactly. The *a*'s have the French sound and the accent is on the second syllable. In defiance of all rules I venture to write the word with an *h* instead of a *j*, because otherwise it is sure to be mispronounced. Genetically it belongs to the same class as *mesa, butte, arroyo, playa,* and others in common use.

* C. F. Tollman: Erosion and Deposition in Southern Arizona Bolson Region. Jour. Geol., vol. XVII, 1909, p. 142.

The bahadas consist primarily of innumerable detrital fans deposited by the streams at the point where they issue from the mountains. In moist countries such fans can not attain large dimensions, for they are soon washed away by the steady flow of the streams. In dry regions, on the contrary, they tend constantly to increase in size. None but the largest streams are permanent; for the great majority come to an end soon after leaving the constricted valleys of the mountains. Emerging from the uplands, their speed is checked so that they deposit their load of waste and are divided into many distributaries. Thus fans are formed in whose thirsty gravel most of the water is lost, while the remainder runs on a few miles farther with constantly diminishing volume until it finally spreads out into thin sheets, forming playas which soon evaporate. Except in the case of occasional floods which reach the main streams and run through to the sea, every bit of material that most of the streams bring down from the mountains is deposited in the lowlands. Thus year by year and century by century the fans grow in size, and finally coalesce into what appears to be a single great slope, a vast apron or glacis surrounding all the mountains, and ever rising higher as the mountains themselves are worn lower. In time the waste from the higher mountains may bury the lower ones, cutting them off at first and forming the gravelly passes which make it so easy to cross the minor ranges at frequent intervals. As time goes on, many small mountains are so buried that they merely stick up as little pointed buttes in the midst of a rising sea of gravel and silt. Doubtless in past ages many hills have disappeared entirely, for the deposits washed down from the mountains to the lowlands have a depth of over 1,000 feet not far from Tucson, as shown by the records of wells dug by the Southern Pacific Railroad.*

Close to the mountains the bahadas consist of coarse material in the form of subangular boulders with a matrix of cobbles and sand. Farther out, as the slope decreases, the boulders disappear, although in some cases they are washed to a distance of 5 miles or more. Then the cobbles diminish in size and finally vanish, leaving only gravel, and that in turn gradually gives place to the fine sand and silt which alone are found in the playas where the slope is reduced almost to zero and the waters come to rest. The bahadas, playas, and half-buried mountains of the southwestern part of the United States reproduce exactly the topographic forms of other deserts in distant regions, such as Syria, Persia, and western China. In all parts of the world these great piedmont deposits preserve full records of the climatic vicissitudes to which they have been subject. Manifestly the nature of the materials laid down under various conditions of climate is bound to vary, even though a certain degree of aridity may have prevailed at all times. If the mountains were at some time denuded of trees by excessive drought, a great amount of soil must have been washed down in ensuing years. If the amount of vegetation became greater than now, and the streams became more constant by reason of greater rainfall, deposition at the immediate base of the mountains must have diminished, while farther away it must have increased. Thus the depths of the bahadas must preserve a record of all manner of changes. In the present volume this subject will not be taken up, because it does not bear upon our immediate problem of *recent* climatic changes, but evidently any comprehensive study of the climatic conditions of the geologic past demands a careful examination of complete sections from the bahada slopes not only of America, but of all parts of the world.

(3) *The Terraces.*—The bahadas by no means always merge into playas, nor do they universally coalesce with one another. In fact, they usually fail to do so. Once all the bahadas coalesced smoothly and merged into playas or flat valley bottoms, but now their smooth slopes come to an end in terraces and are constantly interrupted by small valleys and gullies of recent origin. These valleys may be just wide enough for a small torrential stream, or several miles wide. Their depth may be a few feet or hundreds. Their sides

* Carn. Inst. Wash. Pub. 99, 1908.

may show an unbroken slope, gentle or steep as the case may be, or may be broken into four or five terraces. Practically every waterway, large or small, is bordered by one or more terraces. They form the third of the persistent elements of the landscape. Not so noticeable as the rough mountains, not furnishing a home and land for tillage to the ancient inhabitants like the bahadas, they are in some ways quite as important. Their interpretation, unlike that of the other features, is by no means a matter of general agreement. Therefore, when we have briefly discussed the vegetation of the country, I shall devote a chapter to a consideration of the two opposing theories, climatic and tectonic, which have been advanced in explanation of the terraces.

A

B

C

[illegible] Yuma.
[illegible] Arizona. [illegible] greasewood, etc.
[illegible] Sonora.

CHAPTER III.

THE ARBOREAL VEGETATION OF THE MONSOON DESERT.

A detailed description of the vegetation of Arizona and New Mexico would be out of place in the present volume. Not only does it lie beyond the writer's field of knowledge, but it has been ably done in MacDougal's volume on the Deserts of North America,* and in other publications of the Desert Laboratory. The purpose of this chapter is merely to call attention to one of the peculiar results of the twofold rainy season of the southwest. The result is much more obvious in the warm southern parts of Arizona than in the regions of greater altitude. Hence I shall confine myself chiefly to that region.

To one familiar with the deserts of the Eastern Hemisphere or of other parts of North America, the vegetation of the less elevated portions of southern Arizona, northern Sonora, and, to a less extent, southern New Mexico is surprising. The annual rainfall at Tucson at an elevation of 2,300 feet amounts, it will be remembered, to about 12 inches. The amount elsewhere may be seen by referring to figure 1 on page 10. Few parts of southern Arizona and New Mexico have more than 12 inches of rain, most of the country has less, and Yuma, as is well known, has only about 3 inches. So far as habitability is concerned the country is genuinely a desert. There are several places in Arizona, especially in the southwestern part of the State, where the whole of Massachusetts with its 3,500,000 people could be set down without disturbing a single farm, or cattle ranch, or any other place where people are making a living from the soil as distinguished from mines and railroad enterprises; the same is true of Sonora. Nevertheless the general aspect of the country is green, even in the dry seasons. Most regions having a rainfall of only 10 or 12 inches are bare and treeless, as may be seen in Utah or Nevada, or in Syria and Persia. There arboreal vegetation, away from the water-courses, is almost entirely restricted to insignificant grayish-green forms like sage-brush. In a measure this is due to unrestricted grazing, but by no means entirely; for in places where flocks never graze the bushes are small and rare and trees are unknown. In the southern part of Arizona, on the contrary, bushes are found almost everywhere except on the mountain sides, and the aspect of the desert is distinctly arboreal and verdant. Thousands of square miles are covered with the useless creosote bush, a shrub which grows to a height of from 4 to 6 feet or more, and is thickly studded with small gummy leaves. The individual bushes are commonly 10 or 15 feet apart, and the ground between them is often bare or covered only with a short-lived growth of grass. Nevertheless, the bushes are close enough to one another to give a pronounced green color to the landscape as a whole. In addition to the creosote bush there are numerous larger species of bushes and trees. The most prominent is the mesquite, which sometimes grows to a height of 40 or 50 feet in relatively damp bottom lands. Commonly it attains a height of 15 or 20 feet, and grows in loose groves resembling extensive peach orchards. Among the creosote bushes and mesquites numerous other trees are found, such as the ironwood and several other species of acacia, and the palo verde, whose green bark, tiny round leaves, and dainty yellow blossoms constantly attract attention. Everywhere, too, a profusion of healthy green cacti add to the verdure, some being recumbent, like the smaller forms of the flat-leaved prickly pear, some bushy like the spiny, many-branched cholla, and some assuming the dimensions of large trees, like the saguaro or giant cactus, whose fluted columns are often 40 or 50 feet high. (See Plate 1, p. 34.)

* D. T. MacDougal: Botanical Features of North American Deserts. Carn. Inst. Wash. Pub. 99, 1908.

The peculiarly verdant arboreal character of the desert of southern Arizona and Sonora appears to be due primarily to the double rainy period. In the majority of deserts rain falls only during a single season, which is often the winter, when the temperature is unfavorable to growth. Inasmuch as the winters of the less elevated portions of Arizona do not last long, those portions are favored with a relatively good growth of herbaceous annuals in winter, and also in summer, as is fully described in the paper of MacDougal previously referred to. Trees, as is well known, require a prolonged season of growth. The rains of the brief moist season in most deserts do not store the ground with sufficient moisture to enable the trees to mature their various organs and produce seed. In the region under discussion, however, the winter rains start the growth of trees, and supply sufficient moisture to enable the plants to subsist until the arrival of the summer rains. These lengthen the growing season to a period equal to that in many regions which are much better watered. Of course, moisture is scarce for a long interval during the rainless fore-summer, and the ground is too dry for ordinary trees. Nevertheless, many desert species have become adapted to the double rainy season. Hence, although Arizona is a genuine desert from an agricultural point of view, the scenery of the southern part by no means suggests this. The country is far more verdant than many regions whose agricultural possibilities are much greater.

In the elevated plateau-regions of northern Arizona and New Mexico the vegetation is of the usual type, chiefly grasses, small quick-growing herbs, and low stunted bushes of the sage type. This is due to the relatively small amount of rain in summer as compared with winter, and to the length of the winter, which prevents growth in February, March, and even April. Thus the twofold rainy season is largely robbed of its effect. In the higher mountains, at an altitude of 7,000 feet or more, pine forests, fringed with oaks on the lower border, cover large areas. Here the moisture of the winter remains in the ground so late that there is practically only one growing season.

CHAPTER IV.

THE CLIMATIC THEORY OF TERRACES.

The preceding general description of the climate of Arizona and New Mexico, and of the relation of that climate to topography and vegetation, prepares the way for a consideration of the various lines of evidence which seem to indicate that distinct climatic changes have taken place in post-glacial times and even in the period covered by the written history of the eastern hemisphere. Among purely physical phenomena, unrelated to man or his work, none is so widespread or so important in its bearing on this problem as the alluvial terraces described briefly in the chapter on topography. Until within the past ten years such terraces, if they were discussed at all, were almost invariably assumed to be the result of movements of the earth's crust. As a rule, however, they were dismissed with a word, on the tacit assumption that they were not of sufficient importance to warrant further discussion. W. D. Johnson, and possibly others, had recognized that terraces may originate from climatic variations, not only in glaciated, but in non-glaciated regions.* Nevertheless, the possibility of such origin in specific cases was rarely or never discussed. The first papers to consider the matter with any fullness were two upon Russian Turkestan by Professor Davis and the writer, and another upon Persia also by the present writer. All three were published by the Carnegie Institution in 1905 in a volume entitled "Explorations in Turkestan." Since then the subject has received some attention in the writings of Barrell† and others, but no one has yet definitely attempted to test the climatic theory of terraces by applying it to a definite region in America and working out the agreement or disagreement of the facts with this theory and with its chief rival. Accordingly I shall do this, even at the risk of repeating some things which I have said elsewhere in regard to Asia.

Terraces, although a common feature of the landscape in many arid regions, are not of great importance in themselves. As possible indicators of climatic changes in recent geological times, however, they are of the first importance. Geologists have long been keenly alive to the fact that the interior of our planet is in a state of incessant change which manifests itself in the varied phenomena of crustal movements, the bursting forth of volcanoes, and the transformation of rocks by the development of new magmas or by the processes of metamorphism. Yet, in regard to climate, they have until recently tacitly assumed that, with the exception of a few unique cases such as the Permian and Pleistocene glacial periods, the conditions of the earth have either remained uniform for ages or have been subject only to the extremely slow variations postulated by the nebular hypothesis. Recently, however, a change has taken place, and geologists are beginning to realize that at certain special epochs the climate of the past has been subject to great changes. The discovery of evidences of a Cambrian glacial period by Willis and others, and of a pre-Cambrian period by Coleman, and still more the development of the planetesimal hypothesis by Moulton and Chamberlain, have introduced a wholly new conception. Nevertheless, except for a few tentative suggestions, such as those of Gilbert, Davis, and Barrell,‡ the general opinion still remains that climatic changes are very slow in occurrence, that throughout most of geologic time conditions of practical uniformity have prevailed, that the changes of the glacial period came to an end before the beginning of the historic period, and that since that time the climate of the world has remained uniform. If the conclusions

* W. D. Johnson: The High Plains and Their Utilization. Twenty-first Ann. Rept. U. S. Geol. Survey, part IV, 1901, pp. 626, 628–630.

† Joseph Barrell: The Relations between Climate and Terrestrial Deposits. Journal of Geology, vol. XVI, 1908.

‡ G. K. Gilbert: Rhythms and Geologic Time. Proc. Am. Assn. for Adv. of Science, vol. 49, pp. 1–19.
W. M. Davis: Explorations in Turkestan. Vol. 1, Carn. Inst. Wash. Pub. 26, 1905.
Joseph Barrell: Origin and Significance of the Mauch Chunk Shale. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 449–476.

reached in the following pages are correct, however, changes of considerable importance are still in progress, and there is a strong possibility that throughout the course of the world's whole history climate may frequently have been subjected to conditions of high variability. It may have remained constant for hundreds of thousands of years, but on the other hand it may have changed suddenly at any time. Only by an exhaustive study of all the possible evidences of change can we reach certainty on this point, and only then can we test such theories as those of the relation of the carbonic acid of the atmosphere to glacial periods, the effect of volcanic dust in cutting off the sun's heat, or the effect of solar variations upon climate and thus upon the evolution of life.

TERRACES OF THE TUCSON REGION.

Let us turn now to our immediate problem, the origin of terraces. We will begin with a specific example, taking up first the most recent terraces. Near the city of Tucson the Santa Cruz River flows in a newly cut channel from 100 to 300 feet wide and 12 or 15 feet deep. The channel has been excavated by the stream within the last 25 years. Its edges rise steeply from the sandy river-bed to a flat alluvial plain from half a mile to a mile or more in width. The plain is in part covered with a thick growth of mesquite and in part with irrigated fields. Before the cutting of the new channel and the consequent partial draining of the plain, much of it was covered with sacaton, a species of bunch grass, 5 or 6 feet high, which flourishes only in places where flood water occasionally keeps the ground thoroughly soaked for a time. The alluvial plain, in its present form, can not be of great age geologically speaking, or even as measured by human standards; for Professor R. H. Forbes, of the Arizona Experiment Station, has found pottery in the banks on the borders of the channel at a depth of 10 feet below the plain, and similar finds have been made elsewhere. The pre-Columbian inhabitants of America can scarcely have dug to a depth of 10 feet, or, at least, would scarcely have done so, without iron tools of any sort. Therefore we infer that since the time when pottery was in use the alluvial plain at Tucson has been built up considerably. It scarcely needs the pottery to prove this, for when Americans first settled here, half a century ago, the plain was flooded with water every year, so that sometimes the mail had to be ferried across a mile of water. The floods were not so muddy at that time as they now are, but a certain amount of sediment was carried and was deposited where the water spread out.

The alluvial plain is bordered by a gentle terrace of gravel, 10 to 20 feet high, according to its distance from the stream. The top of the terrace forms part of the main bahada slope on which is located the city of Tucson. At first sight the terrace seems to be far more gravelly than the alluvial plain, but this is not so marked a feature as superficial conditions would indicate. The surface of the plain is everywhere composed of fine silt, but in its interior, as disclosed by the cutting of the river, layers of gravel are by no means uncommon. The surface of the bahada, on the contrary, is almost everywhere gravelly, but its interior contains a large proportion of fine material, partly in the form of ordinary silt and partly in the form of a calcareous silty formation known as caliche. The preponderance of pebbles on the surface is largely the result of the process by which the so-called "desert pavements" are formed.* In an arid country eolian erosion gradually removes the finer materials from the surface, but leaves the pebbles. In course of time the process goes so far that the entire surface becomes covered with pebbles which assume the form of a regular pavement and check further erosion of the underlying fine materials. In the bahada on which Tucson is located the process has not gone so far as to produce a genuine pavement, but it has progressed sufficiently to make the surface much more gravelly

* See Tollman, op. cit. Journal of Geology, vol. XVII, 1909, p. 149.

than the interior, and to show that the bahada is decidedly older than the alluvial plain at the base of the terrace which borders it. The development of the calcareous deposit known as caliche is also a sign that the materials of the bahada are older than those of the alluvial plain.

To the superficial eye it seems as if the bahada which stretches from Tucson southeastward in a splendid green slope for a score of miles toward the mountains were the uniform product of a single period of deposition. Nevertheless, at various points other deposits belonging to higher terraces rise above it. For instance, at the end of the Speedway which runs seven miles eastward from the city, a line of low hills projects above the plain. They are composed of gravel of the same nature as that of the surrounding portion of the main bahada, but of somewhat coarser texture. On every side they are isolated from the mountains by means of the plain of the main bahada; yet it seems fairly certain that they were originally part of a higher, older bahada which bore the same relation to the one on which Tucson lies as that bears to the alluvial plain, or as the alluvial plain bears to the foot or two of materials which have been laid down in the river channel since the last flood. A few miles to the north of the hills, that is, on the north side of the sandy channel of Rillito Wash at the base of the Santa Catalina Mountains, a much more distinct portion of the old bahada is seen. It here takes the form of a regular terrace of the same form as the lower terrace on which Tucson is built. Above it rises still another terrace whose gently sloping flat top presents the unmistakable appearance of a bahada. It is composed of gravel, very coarse here because of proximity to the mountains. Evidently it once extended unbroken to the mountains on the one hand, and far out to the center of the valley on the other. Now it forms a flat-topped and almost isolated plateau connected with the mountains only at one or two points. At a still higher level, traces of a fourth terrace and bahada appear, but are not sufficiently distinct to allow of certain identification.

Similar terraces occur along every stream which I saw anywhere near the mountains during three months' stay in the country. On the minor tributaries and far downstream on the main drainage lines only one terrace is commonly visible, but higher up the number increases along streams of any size. In many cases, similar to that just described, only a single terrace appears at first, but careful examination, even without going farther upstream, usually shows that there are several. As a rule the older terraces are so completely dissected that they have disappeared except in a few favored spots, where they are preserved either as stumps, so to speak, on the lower flanks of the mountains high above the limits of the lowest main terrace, or else as isolated islands in the form of flat-topped hills, such as those along the southwest base of the Catalina Mountains.

Back in the mountains toward the heads of the main streams the number of terraces is commonly four or five. Thus at the head of the Cañada del Oro, on the northeast side of the Santa Catalina Mountains, Dr. MacDougal states that there are five distinct terraces. Lower down in the same valley I saw three, very perfectly developed. On the opposite side of the same mountains the three, or possibly four, main terraces of the Rillito have already been described. In addition to these there is a minor terrace bordering the present flood plain. In the upper valley of the Pantano, a main tributary which joins the Rillito from the south just before that waterway unites with the Santa Cruz, numerous terraces can be seen to the south and southwest of the Empire Ranch at the eastern base of the high Santa Rita Mountains. In Gardner Canyon, for instance, the upper terrace appears as a broad bahada lying close to the base of the mountains, while farther out in the main valley of the Pantano portions of it can be seen as isolated hills with flat tops; like all the rest of the terraces it is composed of coarse gravel full of cobblestones and small boulders. The next terrace is very pronounced, and can be seen over a wide range of country. Where I climbed it, the height amounts to 30 or 40 feet, and the fairly steep slope leading up to the broad flat bahada is covered with loose boulders and cobbles. The third is less pronounced than the second; it is less than half as high, and has a much more gentle slope. Below it there is a little terrace only about 5 feet in height, which scarcely deserves to be noticed. Next comes a fifth, which is the most pronounced of all; it corresponds to the one on which the city of Tucson is built. Below it there is what may be termed an incipient sixth terrace corresponding to the edges of the new channel at Tucson.

TERRACES OF OTHER ARID PORTIONS OF NORTH AMERICA.

Forty or 50 miles to the southwest of the northward-draining Pantano the main branch of the Magdalena River in Mexico drains to the south. Here again terraces are highly developed, as may well be seen at Cocospera (see Plate 1, c, page 34), near one of the old Spanish missions which are so picturesque a feature of all this region. The total number of terraces here amounts to seven, in addition to the terraced edge of the present flood-plain. One of the seven, however, is only 3 or 4 feet high, and is not continuous, so that it scarcely deserves to be counted. Two of the others lie close together and usually merge into one. All alike are composed of gravel and appear to be the same type as those of the other valleys of the region.

Terraces of the kind here described are not confined to the valleys mentioned above; they occur in that of the San Pedro to the east of the Santa Cruz and in that of the Gila to the north. In northern Arizona the Grand Wash in the western part of the State contains one or two terraces which appear to be of the same type, and so does the Kanab Canyon in southern Utah, which I have elsewhere described in connection with the terraces of Persia and Turkestan.* In the northeastern part of Utah the Provo River, which rises in the Uinta Mountains and flows southwestward through the Wasatch Range to Great Salt Lake near Provo, traverses a valley which shows a fine series of terraces of the same type prevalent farther south. The same is true of Kamas Creek, flowing north to the Weber in the same region. In Montana similar phenomena of the upper Yellowstone and other valleys may perhaps be connected with glaciation, but this can not be true of those already described in Arizona nor of those of the Rio Grande, Tularosa, and other streams in New Mexico. Still other terraces which can not be of glacial origin occur in various parts of old Mexico and will be described later. All these are only a part of the cases of non-glacial terracing which the writer has himself seen.

From the descriptions of others it appears that there are many other valleys in the semi-arid portions of America which are similarly characterized by terraces. For example, since the completion of the original manuscript of this chapter the Journal of Geology for October 1910, vol. XVIII, pp. 601–632, has appeared containing an article by J. L. Rich, who describes terraces of apparently the same sort in Wyoming. Mr. Rich has also presented before the Association of American Geographers a paper in which he discusses the process of terrace-making as it has occurred during the last half century. In general he adopts the theories of the present writer as set forth in "Explorations in Turkestan," and in a paper on "Some Characteristics of the Glacial Period in Non-glaciated Regions."†

TERRACES OF FOREIGN COUNTRIES.

Turning to foreign countries, in the publications already named, I have discussed similar terraces distributed from Turkey on the west to China, 3,000 or 4,000 miles away, on the east. In Greece they occur along rivers such as the Alpheios, and appear to have had a share in the burial of the ruins of Olympia.‡ Apparently some terracing process has been very active in the arid or semi-arid mountainous regions of the world in the most recent

* Explorations in Turkestan, Expedition of 1903. Carn. Inst. Wash. Pub. 26, 1905, p. 272.
† Bulletin of the Geological Society of America, vol. 18, pp. 351–388.
‡ The Burial of Olympia, by Ellsworth Huntington. Geographical Journal, London, vol. 36. 1910, pp. 657–686.

geological times, and the activity seems to have persisted down almost to the present day, or even to be still in operation. Clearly the truth can not be ascertained without a realization of the fact that the phenomena are widespread. It is scarcely going too far to say that in the dry, non-glaciated portions of North America and Eurasia regions containing high mountains of unsubdued topography are usually characterized by a peculiar type of terraces which bear so close a resemblance to one another that they all appear to be due to a single cause. Hence the terraces are of great importance because they represent one of the latest and most widespread of geological processes. In attempting to explain them it must constantly be borne in mind that we are dealing with a phenomenon which is as widespread as glaciation, but which has taken place in non-glaciated, arid regions during the same period of time which has seen the intermittent advance and retreat of the ice-sheet from the moist lands of the north.

THE STRUCTURE OF THE TERRACES.

Before proceeding to discuss the two theories of tectonic and climatic origin of terraces, let us first consider the general structure of the terraces themselves. In doing this the facts will be drawn only from a limited area in southern Arizona and northern Mexico, but the general statements apply with equal truth to other parts of North America and to Asia. The upper portions of the terraces universally consist of alluvial material varying in texture from coarse cobbles and boulders to fine silt, according to the distance from the mountains. In the majority of cases the entire terrace is alluvial from top to bottom, although the

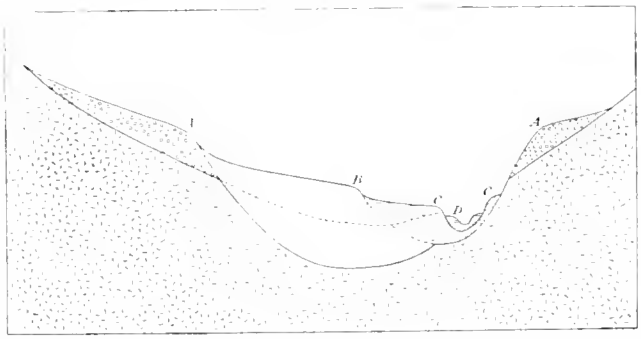

Fig. 5.—Cross-section illustrating the Formation of Climatic Terraces.

different layers may vary greatly in texture, a part, for instance, being composed of coarse gravel, while an underlying layer consists of fine clay. In many cases, however, solid rock crops out below the alluvial material. In such cases it is clear that the gravel which lies on the rock and forms an upper terrace, and that which lies against it at its base and forms a lower terrace, are not of the same age. This can be plainly seen on the right of figure 5, where the deposition of the gravel of terrace *A* was clearly separated from that of *C* by a period of erosion, or in fact by two periods of erosion in this particular case. In other cases, such as that already described at Tucson, a lower terrace may consist of fine silt, while the one just above it is composed of gravel. Here again a period of erosion must have intervened, as is illustrated on the left of figure 5, for otherwise it would not be possible to have an unconformity such as that which exists between the coarser deposits of *B* and the finer ones of *C*. In still other cases the deposits of two contiguous terraces, such as *A* and *B*, are so similar that it is not possible to ascertain whether they were separated by a period of erosion or whether they are parts of a single deposit which was first laid down in sufficient depth to reach the level *A*, and was then in part eroded to the level *B*. Terraces of all kinds, or combinations of the various types, may be found together, and a single terrace may pass from one type to another, as it is followed up or down stream.

All the terraces point to a single series of events. They indicate that, on a small scale, the streams have repeatedly passed through what may well be called cycles. Let us assume that a cycle begins at a time when the streams are engaged in deepening and widening their channels, and let us suppose that the process has gone so far that the rivers are cutting into bed rock more or less rapidly. The next step, no matter what our theory may be, is a change which causes deposition. This proceeds until the valley has been filled to an appreciable depth with alluvial deposits which naturally vary in texture from time to time and place to place. Next there ensues another change which reverses the process. It compels the streams to deepen their channels at first and then to widen them. Constant repetition of these two processes on an ever-diminishing scale has produced the terraces which are now so common. Sometimes the streams have shifted far to one side of the valley or to the other, and have completely undermined the older terraces, which in many cases have entirely disappeared or have been reduced to mere fragments. In almost every main valley, however, some trace of older terraces can be found by careful search, and in all valleys, large and small, the younger ones are visible, provided the region is sufficiently arid and mountainous.

NATURE AND DISTRIBUTION OF TERRACES ACCORDING TO THE TECTONIC HYPOTHESIS.

We are now prepared to test the two chief theories of the origin of terraces in arid regions. As has been said, neither theory has yet been carried to its logical consequences and adequately tested in reference to America. In respect, however, to the Gila conglomerates, which are the gravels of the terraces along the Gila River, Lee* has advocated the theory of tectonic origin, basing his conclusions on personal observation, while Barrell,† on the basis of wide reading and most careful reasoning, has come to the conclusion that they are of climatic origin.

Let us take up the tectonic theory first, and see exactly what type of movements of the earth's crust would be required to produce terraces such as those which we find all over the Southwest. The primary process in the formation of terraces may be considered as deposition. After the valleys have reached a certain topographic stage, which may be roughly defined as mature, there must ensue some change which causes erosion to give place to deposition. The amount of deposition may vary from tens to hundreds of feet, but this is immaterial. Finally, it must come to an end, and must be succeeded by erosion, thus giving rise to terraces. The problem before us is simply this: would it be possible for repeated movements of the earth's crust to give rise to the succession of terraces which we find so frequently in widely separated regions? Alternate periods of uplift and quiescence undoubtedly cause terraces, such as those of the gorge of the Rhine, but do they give rise to innumerable terraces which not only occur in valleys of every type, but are often composed entirely of gravel without a trace of solid rock throughout their entire extent?

Let us follow out the process of terrace-making by earth movements, and see what results are obtained under specific circumstances. For the sake of simplifying the problem, let us assume that the streams of a region are engaged in broadening and slightly deepening their valleys. Let us further suppose that the processes of weathering and erosion have proceeded so far that the main streams have flood-plains, although the minor ones have none. In such a case, the first step toward terracing, according to the ordinary form of the tectonic hypothesis, would be either an uplift of the mountains at the heads of the streams in such a way as to cause excessive erosion with consequent deposition farther downstream, or else a tilting of certain portions of the beds of the streams in such fashion as to lessen the grade and thereby induce deposition. Other possibilities, such as the capture or

* W. T. Lee: Underground Waters of Salt River Valley, Arizona. Water Supply and Irrigation Paper No. 136, U. S. Geol. Survey, p. 115.
† Joseph Barrell: Relations between Climate and Terrestrial Deposits. Journal of Geology, vol. XVI, 1908, pp. 173–176.

beheading of streams, may be suggested, but these are more or less accidental occurrences and can not influence all the streams of a region in the same way. It must be borne in mind that in 99 out of 100 of the terraces which we are trying to explain the first process is the deposition of a considerable thickness of alluvium, generally of a gravelly nature. We may therefore disregard all possibilities except the two just mentioned, which seem to be the only ways in which earth movements can give rise to abundant deposition in the immediate valleys of the streams.

To take the first possibility, we find that an uplift of the mountains would satisfy the requirements imposed by the terraces of Arizona and elsewhere in one important respect. It would steepen the grade of the upper parts of the streams and thus increase the amount of erosion. This in turn would overload the streams in their unsteepened portions, and would cause deposition at the immediate base of the mountains, which is the place where the heaviest deposits actually occur in the regions under discussion. The deposits, however, are not confined to the base of the mountains as they ought to be according to our present supposition. In regions of mountainous uplift the main valleys within the disturbed area are preeminently the scene of active erosion, as may be seen in the case of the Colorado Canyon or the gorge of the Rhine. Such valleys ought to be free from accumulations of gravel; yet we find that the upper Santa Cruz and Magdalena, for example, which according to the theory of mountain uplift should have been steepened and caused to cut gorges, are actually burdened with enormous deposits of gravel which continue far back into the interior of the mountains. The same conditions seem to prevail in all regions where terraces of the kind here described are found.

It is possible to obviate the difficulty just suggested by assuming that the mountainous region has not been uplifted as a whole, but that individual ridges have been uplifted, while the intervening main valleys have remained unaffected. This would certainly explain the occurrence of the gravel in the main valleys. It would not, however, explain the occurrence of similar gravel deposits in practically every one of the side valleys, such as the upper part of the Cañada del Oro north of the Santa Catalina Range and directly among the supposedly uplifted mountains. It would also involve an assumption contrary to some of the chief conclusions of geology as to the nature of crustal movements. It would be necessary to assume in the first place that important changes in the relative attitude of the neighboring parts of the earth's surface have taken place in the very latest geological times without leaving any visible sign of movement, such as fault scarps or gorges due to uplift. It would also involve the assumption that movements of the interior of the earth's crust take place in such a way that all the ridges and elevated parts of scores of mountain systems have been raised so as to steepen the grade of the minor tributaries, while the main valleys remain unchanged. In other words, the assumption is that the internal movements of the earth adjust themselves most delicately to the minor features of the surface, an assumption the exact reverse of the truth.

There is another objection to the theory that the terraces are due to the intermittent uplift of the mountains and the consequent alternation of periods of rapid and slow erosion. The uplift would, of course, occasion active deposition at the base of the mountains, while active erosion was in progress higher up. The cessation of uplift and hence of active erosion among the mountains would leave the streams with comparatively light loads and thus cause erosion to begin in the piedmont region of previous deposition. This would doubtless give rise to terraces resembling those whose origin we are discussing. Directly among the mountains, however, it is evident that if erosion were first active and then slow, and if this process were repeated several times, terraces of rock would necessarily be formed at the same time that terraces of gravel were being formed lower down. While erosion was active the valleys would be deepened; when it became slow they would be broadened. The continual repetition of these processes could scarcely fail to produce a series of rock terraces corresponding to the gravel terraces lower down, but exactly the reverse in phase, for the horizontal portion of the upper terraces would be synchronous with the vertical portion of the lower. Probably such terraces exist somewhere in the world. They are apparently scarce, however, and in the regions under discussion none has as yet been pointed out, although those of the other type are found in scores of valleys. The two kinds are scarcely associated in any such way as they would be if the ordinary terraces were due to uplift of portions of the earth's crust. It seems reasonably certain that, so far as most of the terraces of arid regions are concerned, we must give up the theory that they are due to intermittent uplift of the mountains, for this not only would involve an incredible degree of agreement between lines of drainage and lines of earth movement, but also would demand that terraces of rock should be a characteristic feature of scores of valleys where none are to be found.

If uplift of the mountains is incapable of explaining the terraces, can they be explained as the result of crustal movements which would diminish the grade of the lower portions of the streams? The first step, according to this form of the hypothesis, would be a tilting of the surface of the earth in such fashion as to lessen the grade of the rivers and thereby cause them to deposit part of the load of detritus which they were bringing from the mountains. The process of deposition would continue until the streams had filled up the low parts of their valleys to the point where conditions of perfect grade were obtained, that is, conditions of perfect adjustment of load to velocity and volume. If the process of deposition were sufficiently rapid it would keep pace with the tilting, and would come to an end as soon as the tilting ceased. In that case the cessation of tilting would cause an immediate change in the mode of activity of the streams. They would cease to deposit their loads in large quantities and would tend once more to cut down their channels. Thus terraces would be formed which would possess the character of those which we are attempting to explain. Further tilting would cause renewed deposition, and cessation of tilting would permit the cutting of a second terrace along each stream. If the deposits due to the second tilting did not reach the level of the first deposits, the first terrace would persist with no changes except those arising from ordinary weathering and erosion. Further repetition of the tilting process would of course cause further terraces, provided always that the later deposits did not cover the earlier, and that the times of erosion were not so prolonged as to cause the complete removal of the older deposits.

At the very outset this form of the hypothesis of crustal movements is confronted with the same difficulty as the other form. The terraces are in one sense universal in arid regions, but in another sense they are very local. As has already been said, they are limited to the mountainous regions, and more specifically to those mountainous regions where the topography is still rugged and the elevation considerable. The terraces vary in size in proportion to the height and steepness of the slopes immediately adjacent. They grow higher where the valleys become narrow, as a rule, and lower where the valleys broaden. Sometimes, however, if the narrow parts of the valley happen to be so located that they have a steep grade and are not plentifully supplied with rock waste from tributaries, the case is reversed. Often the terraces die out entirely in the gorges because the grade is such that no deposition took place even in times of the heaviest load, or else because the small size of the valley has allowed all the deposits to be washed out since the last main epoch of deposition. From what has just been said it is clear that the terraces may be a widespread phenomenon in one sense, but in another they are very local, for their size and character depend largely upon the condition of the mountains in the immediate vicinity. This means that the cause, whatever it may be, acts upon each individual river and mountain independently. In other words, general, regional warping of the earth's crust can not be appealed to in explanation of the phenomena. Such warping would cause the streams to be terraced continuously throughout the whole district which was warped, but would not cause the terraces to increase or diminish in size, and even to appear and disappear in accordance with purely local conditions of topography. Moreover, regional warping would cause some streams to be accelerated and others to be retarded, according as they flowed with or against the direction of warping. Therefore its effect would be divided into two classes. In the case of streams which were retarded we should have the kind of terraces discussed in the preceding paragraph. In the many cases where the streams were accelerated, however, we should expect to find young gorges with terraces of rock along their sides. These, as we have already seen, are not found. If regional warping is the cause of the terraces, a given stream ought to behave differently according to the direction in which it flows. The Santa Cruz River heads in the southern part of the State of Arizona. It first flows south for about 20 miles into Mexico, then west around the end of the Santa Rita Mountains, next north for 60 miles, and finally northwest. Terraces of the same type continue from the head clear to the beginning of the northwesterly section, where they finally die out. If any general warping of the crust had taken place, parts of the Santa Cruz would have been accelerated and parts retarded. Therefore we should have portions of the river valley assuming the form of gorges with rock terraces, and other portions where deposition had taken place and gravel terraces had been formed; and the location of these two types would have nothing to do with the topography of the country in the immediate vicinity. No such condition exists, however, and we seem to be forced to abandon the theory of general warping or tilting, whereby the streams were checked and forced to form deposits and terraces.

In view of the preceding paragraphs we are led to conclude that, if the terraces are due to a checking of the streams by tilting, the tilting must have been extremely local in character, so that each stream or portion of a stream was affected individually. Here again we meet difficulties. If some parts of a region were tilted so as to retard certain streams, it is inconceivable that other parts should not have been tilted so as to accelerate the streams, but of this, as has been so often said, we find no evidence. Apparently we must give up the theory of crustal movements, except as a reserve hypothesis to explain exceptional phenomena, or else we must conclude that the interior forces of the earth adapt themselves with the most minute precision to the minor topographic features of the surface, and always act in such a way as to produce the same results upon regions of similar topography.

NATURE AND DISTRIBUTION OF TERRACES ACCORDING TO THE CLIMATIC HYPOTHESIS.

Turning now to the climatic theory of the origin of terraces, we find that it seems to fit all the conditions. Let us take up the matter first from a purely theoretical standpoint. For the sake of convenience, let us assume the same initial conditions as in the preceding discussion, namely, that the streams are engaged in broadening and slightly deepening their valleys. The main streams are supposed to have reached a stage of development where they have formed flood-plains, while the minor streams are without flood-plains and the topography is rugged. Let us assume also that the climate is relatively moist. Under such circumstances the slopes of the mountains will be well covered with forests and with other vegetation; the streams will be numerous, and will be of fairly constant volume without being subject either to excessive floods or absolute drying up, and most of them will discharge into the main rivers, so that much of the sediment which they carry will reach the sea with comparative rapidity. In the absence of any positive knowledge as to the climate of Arizona during the glacial period, we can not say positively that exactly these conditions ever prevailed there, but there can be little doubt that such was the case, for similar conditions still prevail among the high mountains.

If moist conditions, such as have just been described, give place to aridity, many other changes will take place. The forests and a large part of the other vegetation will die; the streams will diminish in volume, many will dry up entirely part of the time, and will fail to reach the main rivers except in occasional floods. The death of the vegetation will lead to the denudation of the mountains, as may be seen on a small scale in certain places in Oregon or the Southern States where forests have been cut and afterward the ground has been burned over in such a way as to kill off the roots and new shoots, or where land has been carelessly plowed in such fashion that the rains have had a chance to wash away the soil. In a country where the climate has become so dry that plants will no longer grow in abundance, there is nothing to check the process of denudation, and ultimately the slopes will become almost absolutely naked, as they are in Persia. Such a condition of extreme denudation, as has been shown in one of the earlier sections of this report, is also characteristic of the lower mountains in Arizona.

The rapid removal of soil from the slopes of the mountains will inevitably increase the load of the streams, and in many cases will overload them. Accordingly, wherever the grade is less steep than on the slopes or in the minor tributaries, the advent of aridity will cause deposition to begin at once, either at the base of the mountains or in the larger valleys. The streams which fail to reach the main rivers, as the majority of those of Arizona now do, must inevitably deposit all the rock waste which they carry. Formerly they bore part of it to the sea, but now none whatever gets there in many cases, and only a small fraction of the former amount in the case of streams which occasionally run through to the main rivers in times of flood. This process of deposition tends to build up deep accumulations of gravel in the valley bottoms and vast fans or alluvial aprons (bahadas) at the base of the mountains. As these deposits increase in size the streams are less and less able to reach the sea. They are obliged to flow for long distances over porous deposits of gravel and silt which are rarely saturated with water and which accordingly act as great sponges. The grade is continually diminished, also, which tends to make the streams spread more widely and therefore evaporate or sink into the ground more rapidly. Thus, so long as aridity continues, the main mountain valleys and the piedmont regions tend to retain all the material which comes down from the mountains. Where the mountains are high and the slopes steep the process of bringing material from them is naturally rapid.

To complete the process of terracing the only requisite is a return to moist conditions. Vegetation will increase in amount, the streams will become more uniform in size from season to season, the gravel deposits will become saturated with moisture, the water of the streams will be less subject to loss by sinking into the ground and by evaporation, and the streams will become longer. Many streams which formerly came to an end at the foot of the mountains will now flow through to the sea. In their upper portions they will be supplied with waste less abundantly than hitherto, because the greater abundance of vegetation will tend to hold in place whatever new soil may be formed. Hence the streams will not be so heavily loaded with waste as previously. They will possess the relatively clear character of rivers in rainy regions, such as the Connecticut or the Illinois, rather than the muddy character of the Missouri or Colorado. Being clear, the rivers and streams will also be ready to become erosive agents at the first opportunity. They will find their opportunity when they leave the mountains and flow out beyond the limits ordinarily reached in the preceding dry epoch. Figure 6 illustrates the matter. Suppose that originally a stream flowed from the mountains at A down into the low country at C, and to the ocean at E. During an ensuing time of aridity, suppose that the extreme limit of floods was D, and that usually the stream entirely disappeared by the time it reached C'; under such circumstances deposits would accumulate as shown in the figure between the lower line passing through C and the upper line passing through C'. The lower line represents the normal profile of a stream. It is concave upward because, after a stream has once attained the thoroughly graded condition characteristic of maturity, the slope steadily decreases from head to mouth. A dry epoch will manifestly destroy the perfect concave curve, for there will be abundant deposition, amounting perhaps to hundreds of feet, at *C*, while at *D* there will be none whatever. Therefore the curve will assume a new form. It will be concave as far as *C′*, but beyond that it will become convex. In other words, beyond *C′* there will be a steeper slope than above it, or than formerly existed beyond *C*. When the climate becomes more moist, and the revived stream flows in full force past *C′* and *D*, and on to the sea, its velocity will naturally be accelerated between *C′* and *D*. As it is not loaded to its full capacity, it will inevitably begin to erode the gravel and silt of its own previous deposits. A gully will soon be formed, and will rapidly work

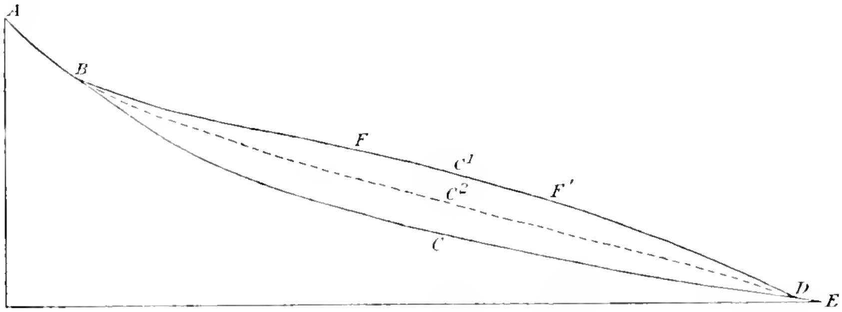

FIG. 6.—Profile of Climatic Terraces.

backward toward *B*. In course of time the stream will once more make its bed concave upward, perhaps at the level C^2. Then it will widen its channel as well as deepen it, and we shall have a flood-plain bordered on either side by a terrace.

TERRACE-MAKING AT THE PRESENT TIME.

The process described above seems to be taking place on a small scale at the present time, although man interposes in a way which makes the matter confusing. To-day, as has been said, the Santa Cruz River flows in a channel from 100 to 300 feet wide and from 10 to 20 feet deep. The channel is cut in a smooth alluvial plain from half a mile to a mile wide. Thirty years ago the alluvial plain was a genuine flood-plain, and there was no inner channel whatever. In times of flood the river wandered over all parts of the plain, flowing very slowly and not eroding at all. At Tucson, as we have seen, the mail was sometimes rowed across half a mile of water, although now the river passes under a bridge scarcely 100 feet long. The water must have carried sediment when it left the mountains, but by the time it reached Tucson it had spread out so much and fallen to such a low velocity that it had deposited most of it. A few miles farther downstream it came entirely to an end as a surface stream, although some underground water seems to have come to the surface and made a new stream at a point farther down toward the Gila. In the last two decades of the nineteenth century man interfered with nature's plans. For one thing he introduced cattle, which ate the grass, and which also made paths. He also dug ditches for irrigation in various places near Tucson, along the portions of the river corresponding to *C′–D* in figure 6. Then, at the end of the eighties, there came some unusually heavy rains. The paths trodden by the cattle, and still more the ditches dug by man, served as gathering-places for the water which had previously flowed in a slow sheet among grasses and bushes. Being confined in a channel the water gained enormously in erosive power and quickly deepened and broadened its bed. One of the first places where this happened was along an irrigation ditch at the San Xavier Indian Reservation, 9 miles south of Tucson. Later it occurred in still worse form at the ditch of Mr. Samuel Hughes, about 2 miles north of Tucson. Subsequent floods enlarged the various channels, which finally coalesced into a single broad channel extending tens of miles above and below Tucson. A record of the whole matter can be seen in Plate 1, figure A, from a photograph taken at the "Point" of the Tucson Mountains, near the railroad station of Rillito, about 17 miles northwest of Tucson. According to the botanists the palo verde trees, *Parkinsonia torreyana*, seen partly embedded in the bank of the channel must have begun their growth at a time when the place where the bottoms of the trunks now stand was the surface of the alluvial plain. While the trees were getting a start and making their first growth, the plain must have remained at nearly the same level. Later, however, it was built up about 5 feet by river deposits, as can be plainly seen. The condition of other trees on all sides shows that the entire flood-plain was here being built up. The length of time during which this process has been going on may be judged from the age of the trees. I cut down the largest of those seen in Plate 1, A (page 21), and counted its rings. They show that the tree began its growth between the years 1670 and 1680 A.D. For about 200 years deposition appears to have predominated over erosion, so that the plain was gradually built up by the addition of 5 feet of silt. Then in a decade or two the slowly accumulated deposits were swiftly washed away, not only here, but for 20 or 30 miles upstream. To turn back to figure 6, it appears as if erosion suddenly began and a channel was cut at several places in the vicinity of Tucson, corresponding to C' in the diagram. Then it rapidly extended upstream and still more downstream, until a continuous channel 30 miles long and from 2 to 15 feet deep was formed. If we assume that this new channel extended from F to F', it is evident that the material which would formerly have been deposited in that region began to be carried below F', thus completely changing the area of maximum deposition. If the channel should lengthen still more the area of deposition would be moved still farther downstream, and might even disappear if the stream finally attained such size as to flow through the region of bahadas into the main Gila River and the sea. This has not happened, however, for great floods such as those of the late eighties or of 1905 are not common. During the relatively dry years from 1906 onward there has been a slight tendency for the new channel to silt up. In other words, the area of chief deposition is shifting upstream once more.

Here, on a small scale, we have an example of the entire process of terrace-making. First slow deposition lasting 200 years, next a rapid cutting of a channel with a marked shifting downstream of the area of deposition, and finally a slight and possibly temporary resumption of the process of deposition in the old area. Man, to be sure, has played some part in the matter, but he has simply served as the means, so to speak, of pulling the trigger which allowed certain natural forces to come into play. If any other cause, such as protracted heavy rains, had gathered the water into a single channel or had increased its amount so that it flowed farther than hitherto and ran down the steeper slope of the convexity below Tucson, the same thing would have taken place. Moreover, another vital point must be remembered. Man alone did not cause the terracing. The cutting out of the inner channel required a number of exceptionally severe floods, and the later slight refilling of the channel demanded a period of diminished rainfall. Possibly the floods would have caused the cutting of the channel even without man's intervention, and certainly the refilling has nothing to do with man. It is significant that this same type of channeling and refilling, this process of terrace-making on a small scale, has occurred at practically the same time, not only on scores of streams in the arid Southwest, but on an equally large number in various parts of Asia, where man's relation to nature has not been subject to any change like that due to the settlement of our own regions. Therefore it would seem that the process of terrace-making is now going on irrespective of man; it may be accelerated or checked by his actions, but it seems to occur primarily in response to climatic variations.

Manifestly, in the case of the little terraces now under consideration, earth movements have had nothing to do with the matter. We have seen that in the past, also, earth movements of sufficient magnitude to produce the large terraces of earlier times apparently could not have occurred without leaving evidences in the way of fault scarps and gorges. Climatic changes, on the contrary, are positively known to have taken place, for no one doubts that when New York was covered with ice the climate of Arizona was different from what it is to-day. Furthermore, climatic changes would act in exact agreement with the topography. That is, if a mountain range were high and massive, and a change of climate toward aridity were to kill a large amount of vegetation upon its sides, much soil and gravel would be washed down and deposited at the base. A return of moist conditions, on the contrary, would lengthen the streams and cause channeling. Thus high, steep mountains would be accompanied by lofty terraces. In the case of low, gently rounded hills, on the other hand, aridity might cause the death of vegetation, but the soil would not be washed away with anything like such great rapidity as upon mountains of steeper slope. Thus no terraces, or only low ones, would be formed. Every part of a region would be acted upon equally, without respect to the topography or to the direction or size of the streams, and the effect would everywhere be of the same kind, yet the results would vary in harmony with the topography. Altogether it seems as if the climatic theory fitted all the facts so far as they are yet known, while the theory of earth movements meets obstacles at every point. The matter still needs a vast amount of study, however, especially along the lines of a careful mapping and measuring of the terraces of a few chosen regions. Much light might also be obtained by a careful investigation of the many channels which have been cut by various rivers since the opening of the Southwest to settlement by the white man.

THE CORRELATION OF TERRACES.

If the theory of the climatic origin of terraces be accepted, we are at once confronted by the problem of the correlation of those in various parts of the world. As yet it is too early to attempt much along this line. Nevertheless, it is worthy of note that in number, arrangement, degree of weathering, and other characteristics, there seems to be a fairly close agreement between those of America and of Asia. Undoubtedly the number of terraces varies considerably, but the variation apparently follows well-defined rules. In general the number is greatest among lofty mountains in regions of pronounced aridity. Where the relief diminishes, or where the climate is less arid, either because of greater precipitation or because of lower temperature and less evaporation, the number of terraces becomes less. In the districts of maximum development, such as the higher mountains of southern Arizona or the lofty mountains of Central Asia, the common number is five. Elsewhere it diminishes to two. Such a discrepancy does not mean a different periodicity in the various regions. It simply indicates that from the geological point of view terraces are ephemeral. In regions where the mountains are low the amount of deposition may be so small that terraces of different ages appear as parts of a single formation, or the entire body of some terraces may be carried away by erosion. In regions of only slight aridity erosion may be so active during the erosive portion of a terrace cycle that all the deposits are carried away. That such occurrences take place is proved by the fact that even where the maximum number of terraces is found in some valleys, others in close proximity show only two or three. Moreover, in a single valley some portions have five terraces, and others only two, three, or four. One can often trace a terrace upstream and actually see it disappear, either coming to an abrupt head, coalescing with an adjacent terrace, or simply being lost by erosion.

The alluvial terraces, both of Asia and America, are evidently due to a series of changes of decreasing intensity. The first suggestion that presents itself is that they may represent the various epochs of the glacial period. This does not seem probable, however. In the first place, the youngest terraces are far too new to have anything to do with the last glacial epoch. In the second place, there is too much difference in size between the first and the last to permit the supposition that each of them represents a main epoch. Finally, the oldest terrace does not show sufficient signs of age to warrant the belief that it is as old as the first of the known glacial epochs of the Pleistocene period. It is much worn and eroded almost everywhere, and in many places it has been entirely removed, but its materials are weathered and decayed to only a moderate degree. It seems probable, therefore, as Penck has suggested in regard to those of Asia, that the oldest terrace may represent the last glacial epoch, and that the others represent the post-glacial stages, or minor epochs of glacial retreat, of which there is an ever-increasing abundance of evidence, not only in the Alps and Scotland and other parts of Europe, but in America. Inasmuch as man is known to have existed prior to the last great glacial epoch, the terraces, if our conclusions are correct, preserve the record of a series of climatic changes which have played a part in shaping human destiny. If the oldest terrace dates back no more than 30,000 years, more or less, to the last glacial epoch, the youngest can not be more than 2,000 or 3,000 years old at most, and may be much less.

CHAPTER V.

THE FLUCTUATIONS OF THE OTERO SODA LAKE.

Variations in the level of lakes without outlets are universally recognized as one of the easiest and most accurate methods of determining changes of climate. The well-known monographs of Gilbert and Russell on Lakes Bonneville and Lahontan have shown that during the glacial period the inclosed salt lakes of Utah and Nevada expanded, apparently by reason of the same increase of precipitation or decrease of temperature which caused the formation of the vast continental glaciers of northeastern America and northwestern Europe. Further researches have proved that other salt lakes, not only in the arid Southwest of the United States, but throughout Asia, expanded similarly. Many of the old lake basins, however, even in America, have not been accurately described as yet; and in most of them little attention has been paid to evidences of minor fluctuations since the last great expansion, which presumably took place synchronously with the last or Wisconsin advance of the ice-sheet. Evidences of such minor fluctuations exist in various places, one of which, the Otero Soda Lake, will be described in this chapter. Unfortunately in this case, as in almost all others, we have no means of assigning exact dates to the various stages of the lake. The only North American lakes where that is yet possible, even in the most imperfect degree, appear to be those of the group immediately surrounding the City of Mexico. They will be considered later, in a chapter devoted to Mexico. Meanwhile we shall direct our attention to the minor fluctuations of the Otero Soda Lake and to the accompanying formation of large expanses of gypsum dunes. We shall find that these indicate that the change from the climate of the last glacial epoch to that of the present does not appear to have proceeded by regular steps according to the old supposition. On the contrary it seems to have been marked by pronounced pulsations. The minor strands apparently do not mark mere stages of retrogression, but distinct periods of advance separated by times when the water fell to decidedly low levels.

Before discussing the features which bear on our immediate problem of recent climatic changes, a short description of the Otero Basin in general will be in order, partly to give the setting of what follows, and partly because this region has been discussed relatively little. My study of the basin in the spring of 1911 was made in company with Mr. E. E. Free, who at that time was engaged in an investigation of potash deposits on behalf of the Bureau of Soils of the United States Department of Agriculture. I have drawn freely on his observations and on the results of his work.* I take pleasure in here expressing my thanks for his courtesy.

The Otero Basin lies at an altitude of a little over 4,000 feet between two ranges of fault-block mountains in the central part of southern New Mexico. The mountains run north and south, and may be considered as disconnected continuations of the eastern portion of the Rockies. The eastern range has an altitude of about 9,000 feet in the Mescalero portion near the Otero Lake, while farther north in Sierra Blanco, or Capitan, it rises to 13,000. The range is bounded on the west—that is, on the side toward the basin—by a steep fault scarp. At the top lies the maturely dissected plateau described in the preceding chapter on the physiographic form of the land. Toward the north the plateau rises into the well-dissected slopes of Sierra Blanco, while toward the east it falls off gradually to the Staked Plains of eastern New Mexico and western Texas. With these portions,

* E. E. Free: The topographic features of the desert basins of the United States. Bul. 54, U. S. Dept. Agr., 1914.

however, we are not concerned. The fault scarp which forms the immediate eastern boundary of the Otero Basin must limit our investigations. This escarpment shows evidence of two great periods of faulting and one minor period. Inasmuch as the strata of the uppermost parts of the plateau are Permian, the earliest faulting may have taken place in the Triassic or Jurassic eras. Cretaceous strata, however, lie on the back slope of the plateau. Hence the main faulting can not have taken place until late in that era or in the Tertiary. After its occurrence the uplifted region was worn to a condition of maturity, after which it was again raised by pronounced faulting at some time in the Tertiary era. This movement, however, by no means brought the plateau to its present level. This was not accomplished until the original fault scarp had been dissected into deep valleys, its top had been battered back 2 or 3 miles from its original position, and its foot had been concealed under a deep apron of piedmont gravels. Then renewed faulting occurred and the piedmont gravels were cut in two, probably along nearly the same line where the original faulting had taken place. To-day the old piedmont gravels of the uplifted block can be seen as a much dissected terrace lying at an altitude of about 1,000 feet above the edge of the present plain. Below the terrace the topography is highly rugged and youthful; above it, for a space, the topography is still somewhat rugged and may be considered in the early stages of maturity; while still higher, upon the main plateau, as we have seen in an earlier chapter, it is thoroughly mature. The date of this last main faulting must be somewhere in the late Tertiary, but the process is probably not yet complete. At the very base of the escarpment, from Alamogordo on the south to La Luz, 5 miles to the north, I traced a little fault scarp of very recent origin, and further investigation would probably show that it extends much farther. The movement at the time of the last faulting was in the same direction as during the major faultings of earlier times, that is, the eastern side was uplifted. The piedmont deposits at the base of the mountains were cut in two, and the eastern part now stands from 10 to 20 feet higher than the western. Taken as a whole, the phenomena of the eastern side of the Otero Basin are surprisingly like those of the eastern side of the basin of old Lake Bonneville, at the base of the Wasatch Mountains near Salt Lake and Ogden. In other respects, also, the two basins show marked similarity.

On the west side of the Otero Basin the San Andreas Mountains (and also apparently the Organ Range, farther to the south) assume the form of sharply tilted fault blocks, with a precipitous escarpment forming the front slope and facing toward the east. The tops of highly inclined Pennsylvanian limestones form the back slope which descends to the Journada del Muerto east of the Rio Grande. Here the tilting of the block has been so great that all semblance of a plateau or of an earlier topography has been destroyed.

The floor of the Otero Basin has been deeply covered with deposits just as has the floor of practically every basin in arid regions. The total depth of the filling is unknown, but a railroad well at Alamogordo, near the edge of the basin, was sunk to a depth of 1,004 feet without reaching the bottom of the irregular succession of thin beds of fine gravel, sand, and clay which compose the greater part of the basin deposits. These deposits now form a large plain, very flat in the center and rising gently toward the edges, where the materials change from saline deposits, silt, and clay to gravel. The width of the basin from east to west is about 40 miles in the widest part; the length is over 100 miles. On the south the plain rises gently to a flat divide and then falls away once more toward El Paso and the Rio Grande. On the north it rises more rapidly after the main level portion has been left behind, and ultimately it merges with the great plateau of central New Mexico. The main line of drainage from the plateau to the basin floor is occupied by a very recent lava flow which has sometimes been supposed to date back no farther than the beginning of historic times. It begins in the vicinity of Carizozo and continues southward nearly 60 miles.

Manifestly a basin such as that of Otero must contain a lake if the rainfall is sufficiently heavy. Since the total precipitation of this region, however, is only 10 inches per year on an average, and since the filling of the basin with waste has made the bottom very flat, no permanent lake can now exist. The water which runs down from the mountains during the winter rainy season or during the sudden thunder-showers of summer spreads out in shallow sheets and soon evaporates. The so-called Otero Soda Lake is really one of a series of large playas having a length of about 40 miles north and south, and a width of 6 miles or more. On all sides except the west other smaller playas, several times in a year, are similarly filled with water which soon evaporates, leaving white plains of soda and gypsum. During the glacial period the area covered by all the playas appears to have been included within a single great lake, which was probably 60 miles long and 30 wide. The evidence for this is found in certain old strands, plainly visible at the base of the San Andreas Mountains on the west side of the basin. These have never been studied with care, and my visit was too brief to allow of more than a cursory examination. They are visible in many places, however, and can be seen extending almost unbroken for 20 miles or more. The lowest and most prominent lies over 200 feet above the present level of the main playa. Above it at intervals of from 40 to 80 feet three others can be seen. On the east side of the basin none of the old strands are visible. Possibly they were small and insignificant because of the extremely gentle slope of the plain on this side, and have been concealed by the large amount of débris which, since their formation, has been washed down from the high plateau. Even on the west side, where the mountains are far lower and less extensive than the plateau to the east, great fans of gravel have been washed out from all the canyons, burying the bottoms of the cliffs along the old strands, and in many cases completely concealing the cliffs themselves. This subject, together with that of a possible outlet to the south at the time of the lake's greatest expansion, must be left for future study; so, too, must the interesting question of the relation of the more recent phases of faulting and uplift to the times of expansion of the ancient lake. All these, important as they are, do not bear on our present problem. The one essential fact is that the old strands seem to furnish strong evidence that in former times the basin was occupied more than once by a lake whose extent was far greater than that of the present playas. Almost without further proof we may, I think, assume that the epochs of expansion must have coincided with the glacial epochs of more northern regions. The importance of this lies in its indication that during the glacial period the climate of North America changed almost as much in the warmer, drier portions of the continent as in the colder, moister portions. We can not yet say with assurance whether the strands represent the main epochs of the glacial period, or whether, as is more likely, at least part represent the well-known post-glacial stages which have been so much studied of late in the Alps, Scotland, and elsewhere. Whatever be their exact age, it is evident that they belong to the most recent geological times, and that any changes which have taken place since their formation are sufficiently recent to fall within the period of man's probable presence in America.

Unmistakable evidence that such changes have actually occurred in the most recent post-glacial times is found in certain minor strands of the old lake and in a series of gypsum dunes of various ages. When the playa or Soda Lake is at its greatest extent, its temporary waters are deep enough to be raised by the wind into little waves of sufficient strength to cut a tiny bluff, which at the southeastern corner of the playa has a height of about 2 feet. Above the little bluff lies a terrace 100 to 200 feet wide. Like the bottom of the playa itself, the terrace is covered with crystals of soda and gypsum, but these saline deposits are not fresh like those of the playa, and they are studded with vegetation, indicating a considerable lapse of time since their deposition. At rare intervals the water may even now come up over this terrace, but scarcely for long enough periods or to sufficient depth to allow the waves to cut so steep and pronounced a bluff as that which rises to a height of 15 or 16 feet back of the terrace. Therefore we infer that at some time not more than a few hundred years ago the water must have stood higher than now, and at such a level as to cover the terrace and cut a well-defined bluff at a level about 4 feet above that of the floor of the playa. If the lake rose to this level it must have contained water most of the time, for it would scarcely be possible every year for evaporation to remove 4 feet of water in the few months which intervene between the end of one rainy season and the time when the lake would be replenished by the rains of the succeeding season, whether it be summer or winter.

The top of the bluff overlooking the 4-foot strand forms another terrace, like the one above the present strand, but much older and more covered with vegetation. Back of this, and at an altitude of about 20 feet above the floor of the playa, a third small bluff rises about 10 feet. It clearly marks the strand along which the lake rested at some time hundreds of years before the day of the 4-foot strand. At that time the lake was evidently much larger than the present playa, and was so deep that it can not possibly have been subject to complete desiccation. Back of the 20-foot strand there may possibly be still another belonging to times much more recent than the main strands 200 feet or more above the lake. This doubtful third member of the group of minor strands lies about 60 feet above the floor of the playa. I saw evidence of it only at the southeast corner of the playa, where a low bluff and a line of gypsum dunes run parallel to the present shoreline at a distance of from a third to a quarter of a mile from it; they seem to indicate another old strand, but the evidence is not sufficiently clear to permit certainty. Nevertheless, even if we omit the 60-foot strand, those at elevations of 20 and 4 feet are sufficient to show that in times long after the end of the glacial period the Otero Lake has varied in size, apparently because of distinct climatic fluctuations. The strands, however, do not suffice to show whether the fluctuations were merely pauses on the way toward aridity or were distinct periods of increased moisture following times of aridity.

The most peculiar feature of the Otero Basin, and one of the most significant from a climatic point of view, is the unique dunes of pure white gypsum, the "White Sands," as they are called. Along the east side of the main playa they form a large tract nearly 20 miles long and 10 wide in places. The dunes are like the ordinary type in shape and movement. Their peculiarity consists in the fact that they are composed of almost pure gypsum, which gives them a dazzling white appearance. When the playas become dry in the rainless foresummer or in the fall the strong southwest winds which then prevail sweep across the smooth expanses and pick up clouds of gypsum crystals which have been laid down by the diminishing water. These are swept beyond the limits of the playas and are there heaped up into dunes ranging from 5 to 40 feet in height. In course of time the dunes are gradually moved forward by the winds, while new ones form behind them. At present the area of fresh dunes is constantly increasing by the blowing forward of the gypsum sands. For example, at the plaster mill a few miles southeast of Alamogordo, and at many other places along the eastern margin of the dune area, the sand can be seen advancing like a great white wall. At some points it is overwhelming bushes and small trees, which in many cases are completely buried, only to reappear at length behind the dunes when the winds have swept the gypsum beyond them. At other points the White Sands are encroaching upon old roads, some of which can be seen buried to a depth of 20 feet. An old stage-driver informed Dr. MacDougal that when he used to drive the overland stage through the Otero Basin in the early eighties he was accustomed to water his horses at a well on the eastern edge of the dune area. Now, however, the well is hidden in the midst of the moving sand, a mile or more from the margin.

This rapid movement of the dunes does not appear to have lasted for any great length of time, probably for no more than a few score or a hundred years. There is no means, however, of judging exactly how long it has lasted, but if there has been an advance of a mile in scarcely 30 years, it seems probable that the dunes would have spread farther than the present limits if equally favorable conditions had prevailed for any great length of time.

The part of the White Sands which is now advancing is not the main body of the dunes, but merely a small, superficial portion. The main body is of the same type as the portions now in motion, but the sands are partially fixed by scattered bushes and other small forms of vegetation. Therefore they do not move. In some places it can be seen that in recent times certain portions of them have been freed from the restraint of vegetation, and have begun to move, adding their quota to the supply of sand derived from the gypsum crystals of the floor of the playa. Clearly the older portion of the White Sands, which is decidedly the major portion, was at one time in motion. At that time the climate must have been approximately as dry as now. Then came a time of changed conditions, when the moving dunes were fixed. In certain cases, such as the shores of the Atlantic Ocean in Massachusetts, or the south shore of Lake Michigan, dunes become fixed because they are driven so far from the source of supply that new sand is not furnished in sufficient quantity to prevent the growth of vegetation. In such cases the dunes close to the abundant and constantly renewed supply of sand along the shore can not become covered with vegetation simply because there is such a constant influx of sand, although vegetation would quickly appear if the amount of sand brought in by the waves and wind should diminish. Consequently we find the dunes more and more covered with vegetation as we proceed inland, until a few miles back from the coast they are completely fixed. Among the White Sands, on the contrary, the conditions are quite different. Here there is no gradation from fixed to unfixed dunes. The two types exist side by side, both at the outer edge of the dune area and at the inner edge close to the playa. Everywhere the new moving dunes are overriding the old stationary ones. The only explanation seems to be either that the supply of gypsum has recently increased or that the amount of vegetation has decreased so that the fixed dunes have in part become free. Either alternative demands a change of climate. The supply of gypsum would be greatly increased by a diminution in the amount of water flowing into the lake. If a considerable portion of the floor of the playa were covered with water, as happened at the time of the formation of the 4-foot strand, the supply of gypsum would be much less than now, for at present practically all of it comes from the floor of the playa during the dry season. If the rainfall were great enough to change the playa into a shallow lake, the amount of moisture among the dunes would probably be so great as to cause the growth of vegetation, and thus the dunes would be fixed. In other parts of the world such an increase in vegetation followed by a later decrease seemy to be sufficient to cause the fixation and freeing of dunes without any change in the suppls of sand. I have seen instances of this in several places, especially in the desert south of Palestine near Beersheba, and on the borders of the great desert of Transcaspia. Whether the twofold aspect of the White Sands is due chiefly to a change in the supply of gypsum or to a variation in the amount of vegetation, its ultimate cause seems to be the same. The older phase seems to indicate a period of aridity much like the present; the fixation of the dunes apparently points to a greater supply of water and a higher stand of the lake; and the free dunes of the present are in motion because the climate is dry, the lake has become a playa, and the amount of vegetation is limited. Here, then, we seemingly have evidence that the last series of climatic changes has not been a mere increase in aridity, broken by a period of uniformity, but has been a pulsation from dry to moist and back again to dry.

Two deposits of gypsum older than those just discussed appear to be the remains of earlier fields of dunes, which in their day were like the present White Sands. One of them, called by Mr. Free the Intermediate Gypsum, still shows the characteristic topography of dunes, together with occasional traces of cross-bedding. It covers about the same area as the modern Sands, and can frequently be seen coming out from under them and extending for half a mile or so. The sharper forms of the dunes have been smoothed off, and a considerable amount of solution has removed much of the gypsum from the outer surface, leaving only the impurities in the form of soil. On the gentle slopes thus formed, and in the small but important supply of soil, vegetation of a grassy type has established itself and is able to persist even in a dry time like the present.

Underneath the Intermediate Gypsum lies the Tularosa Gypsum, as it has been named by Mr. Free. In this the typical dune topography has completely disappeared, as has the cross-bedding. Nevertheless the eolian origin of the deposit is quite well established by the sun-cracks, rounded grains, and other characteristics which Mr. Free has detected under the microscope. The Tularosa Gypsum is much more extensive than the others. On the east it extends nearly to the foot of the mountains and is often found buried under a thin layer of alluvium recently brought down from the mountains. A similar deposit, but probably of considerably greater age, is also found high on the flanks of the fault scarp which bounds the Otero Basin on the east. It forms part of the old basin deposit of piedmont gravel, silt, and clay which was uplifted 1,000 to 2,000 feet at the time when the last great fault occurred.

Two possibilities suggest themselves in regard to the origin of the Intermediate and Tularosa beds of gypsum: The first is obviously that they indicate periods of aridity like the present, and that their relation to one another and to the later gypsum is the same as that of the free and the fixed portions of the White Sands. The other, suggested by Mr. Free, is that the older dunes were formed as a narrow strip on the immediate edges of a lake which was in gradual process of desiccation. As the lake retreated it was always bordered by a strip a mile or two wide where it had laid down gypsum. From this a narrow band of dunes was formed. The dunes quickly became fixed by vegetation, since the climate, as indicated by the size of the lake, was moister than now. Thereafter they remained unchanged except for the normal processes of weathering. On the lakeward side new dunes were continually in process of formation, followed by fixation, thus continually broadening the dune area in proportion to the retreat of the lake. Inasmuch as we can not follow the Intermediate and Tularosa gypsums under the White Sands we can not tell whether they extend as far as the borders of the modern playa, nor can we ascertain whether in the interval between their formation the lake expanded. Hence we can not choose between the two theories. The fact that the two divisions of the White Sands apparently represent distinct pulsations rather than pauses in climatic change affords a presumption that the same is true in the other cases.

CONCLUSION.

The general conclusion of the whole may be summed up in the words of Mr. Free in the report already referred to:

"The whole history of Lake Otero and of the period since its disappearance is a record of great and continuous climatic changes, with major fluctuations indicated by the variations of the great ancient lake and its deposits. On these fluctuations are superposed many series of minor pulsations, the greater of which can be read in the triple record of changing topography in lake, dunes, and arroyos. To assign a time scale to these various changes and to date them in years or centuries is not easy, but it is probable that something can be done by careful comparative study of various lines of evidence and of various regions. In general it can be said that the Otero Basin shows the kind of climatic fluctuations which Huntington's work has shown to be typical, namely, large, long-period pulsations, upon which are superposed series after series of smaller pulsations of less and less amplitude and shorter and shorter period."

CHAPTER VI.

THE RELATION OF ALLUVIAL TERRACES TO MAN.

From the purely physical phenomena of fluvial terraces, lacustrine strands, and sand-dunes we have been led to a broad generalization as to the pulsatory nature, decreasing intensity, and present continuance of post-glacial changes of climate in the arid portions of America. From the same lines of evidence a similar conclusion has been reached as to the temperate portions of Asia and the lands surrounding the Mediterranean Sea. In the Old World, however, it has been possible to supplement physical evidence by a large body of historical and archeological data, together with traditions and legends, and thus to determine the approximate dates of some of the main climatic events and to discover some of their effects upon man. In general we are probably safe in assuming that the effect of a given type of change upon man will be essentially the same in corresponding parts of the two hemispheres, but this needs careful testing. The Asiatic dates, on the other hand, do not necessarily afford any clue whatever to the dates of similar climatic changes in America. Hence our next step must be to find out the relation of man to the changes of climate whose existence we have inferred in America and then to determine the dates. It must be constantly borne in mind that the belief that changes have taken place at certain times and in certain ways in the Old World by no means involves a similar belief in respect to the New World. Three possibilities present themselves. In the first place, granting that pulsatory climatic changes have taken place in both hemispheres, it is possible that those in America came to an end long before those in Asia and thus had no influence either upon the Europeans who came in the wake of Columbus or upon the ancient inhabitants who preceded them. In the second place, changes may have taken place in the climate of both hemispheres similar in kind, but by no means synchronously. They may even have been of opposite types, America becoming dry when Asia became moist, and the reverse. Finally, there is the third possibility that all the continents, or at least all the temperate regions of the northern hemisphere, have been subject to the same type of changes at essentially the same times. Leaving the matter of dates for future consideration, let us attempt to determine whether any one or more of the changes of climate which we have inferred to have taken place in America occurred since man reached a stage of culture such that he inhabited permanent villages or towns whose traces still remain. The importance of this subject is so great that we shall investigate it at length, and shall in many cases enter into minute details of evidence in widely scattered regions. I shall endeavor to set forth the facts in such a way that the reader can frame his own answers to three chief questions. First, has the climate of America changed since the primitive inhabitants built the ruins which now abound in the Southwest and Mexico? Second, if it has changed, do the ruins show evidence of changes in more than one direction or at more than one distinct epoch? And third, do the inferred changes seem to have had effects at all comparable to those which seem to have taken place in Asia?

Let us first take up the specific problem of the relation of man to the alluvial terraces which hold so important a place among the purely physical evidences of pulsations. If we accept the theory of the climatic as opposed to the tectonic origin of the terraces of the Southwest, the finding of pottery or other traces of human occupation, either within the body of a terrace or persistently upon some terraces and not upon others, may be significant. In regard to the second point, the finding of traces of human occupation on some terraces and not on others, the data are too scanty to warrant any conclusion. My own observation shows that ruins of prehistoric (pre-Columbian) villages are rarely found upon the present alluvial flats—that is, upon the plains formed by the rivers in the most recent period of deposition. Except far downstream in the neighborhood of broad playas, ruins of any great age appear to be found always on terraces just above the plains of fine silt. This fact, however, possesses no special significance, for the location may have been determined by motives of sanitation or by the desire not to encroach upon arable land.

The location of buried pottery is much more significant. The finding by Professor Forbes of ancient pottery under 10 feet of alluvium in the banks of the newly formed inner valley of the Santa Cruz at Tucson has already been mentioned. Another occurrence of this same nature is described by Mindeleff in the Thirteenth Annual Report of the Bureau of Ethnology, 1891–92, pp. 239–240. In the valley of the lower Verde, one of the northern tributaries of the Gila, the river has recently excavated a channel, leaving the old flood-plain as a terrace, just as in the case of the Santa Cruz. While the process of erosion was in progress, Mindeleff was so fortunate as to see and photograph an old irrigation canal which had been buried beneath 10 feet of alluvium, and was now once more exposed by erosion, only to be washed away forever in the course of a few months. He estimates that the silting up of the valley bottom and the burial of the ditch to a depth of 10 feet must have taken at least 150 years, and may have taken several times as long. How long a time elapsed between the completion of the process of deposition and the inception of erosion is entirely problematical. It may have been anywhere from 10 years to 10 centuries.

The examples thus far given have been from a small area in southern Arizona. (See map, frontispiece.) In northern New Mexico, 400 miles away, I chanced upon a similar example. About 6 miles north of Santa Fe and 3 miles south of the modern pueblo village of Tesuque, Mr. Vierra, an artist of Santa Fe, pointed out a place on his ranch where pottery and ashes have been buried to a depth of 6 feet under alluvium and have since been exposed by the cutting of the stream to a depth of 15 feet. In the steep face of the terrace thus formed we found the vestiges of human occupation so thickly scattered as to show that once a small village must have been located here. It stood in the angle between the main Tesuque stream and a small tributary from the southwest, and pottery is found in the terraces of both streams. I happened at the time to be with Mr. Kenneth M. Chapman, secretary and artist of the School of American Archeology at Santa Fe. He kindly examined the pottery and states that it belongs to the present Tesuque type, and not to the prehistoric Pajaritan type found in the older and more important ruins of the region. This means that since the Tewa stock, to whom the Tesuque Indians belonged, came to this region, probably 700 to 800 years ago, there has been time for a village to be founded and occupied long enough to form an accumulation of pottery and ashes. Then the village was abandoned and floods covered it with 6 feet of silt, after which the streams changed their mode of action sufficiently to cause the erosion of a broad inner valley and the formation of a terrace 15 feet high. We can not say with assurance that man's actions may not have had a part in causing erosion to begin, but inasmuch as man has occupied the region continuously from the times of the Pueblo Indians through that of the Spaniards and Mexicans to that of the Americans, the relation of man to the country has not changed in any such sudden way as has been the case in southern Arizona. Yet even there we saw that, although man had a hand in causing terracing, he served chiefly as a means of setting natural forces in operation rather than as a new force. Heavy rains were needed before any terracing could take place, even in southern Arizona, and in northern New Mexico it is still more probable that the terracing was due to natural changes causing variations of rainfall.

As a final example of the relation of the terraces to man I shall describe the conditions in the Tularosa Valley of southern New Mexico in the plateau east of the Otero Basin. The valley begins a few miles north of the summer resort known as Cloudcroft, and extends northwestward past the Indian agency of Mescalero, then westward and finally southwestward to the edge of the escarpment, where it debouches upon the plain of the Otero Basin. Throughout its course it is characterized by alluvial terraces. In the upper, more mountainous portions of the valley the number of terraces reaches five, while lower down the number diminishes. At the present time no continuous stream flows from end to end of the valley, although temporary streams flow for short distances here and there. At some earlier time a continuous stream probably flowed the entire length of the valley, for the main terraces are well developed and continue many miles, as if cut by a strong flow of water. When such a flow existed the valley bottom was doubtless occupied by a gravelly river channel having a regular, graded slope from end to end. Now, however, under the influence of the last epoch of relatively intense aridity, the valley floor has been filled with alluvium in such a way as to produce well-marked irregularities. Wherever a tributary has brought in an unusually large amount of waste, the feeble stream of the main valley has spread this downstream for a short distance, but has been unable to carry it away. In the deep deposits of silt and gravel thus formed the water of the main stream sinks into the alluvium and disappears, only to come to the surface once more at some point where the depth of the alluvium is less. In this way, as will readily be seen, the valley bottom has been divided into a series of relatively level portions where abundant alluvium has been deposited, and a series of relatively steep slopes where the abundant supply of alluvium has ceased and the stream which should carry it away has disappeared. Often, as one rides down the valley, a plain a quarter to a half mile wide and several miles long is encountered, which seems at the lower end to drop off almost in a slope that would be called steep. The effect, indeed, as one looks down the valley from the middle of the plain, is as if the bottom of the valley were genuinely dropped down to a lower level. Even to the unscientific observer it is manifest that if the supply of water should be sufficient to maintain a continuous stream, erosion would at once attack the steep slopes between the plains. As a matter of fact this process has already begun within the last 2 or 3 decades. At various points deep gullies, one of them with a depth of nearly 50 feet, have been cut, and a series of years of heavy rainfall would cause them all to be prolonged, both upstream and down, until a continuous gully was formed. The succession of events here is exactly the same as in the Santa Cruz Valley, near Tucson, hundreds of miles to the west. The chief difference is that here the part played by man is relatively unimportant: even without man's intervention climatic forces have begun to form a terrace. Apparently the last quarter of a century, from about 1885 onward, has been a period when heavy rains were on the whole more numerous than for many decades, or possibly several hundred years previously.

In ancient times the Tularosa Valley contained at least two villages. One of these was located in the broadening of the valley where the Mescalero Indian agency employs about 20 white men and women to take care of about 350 semi-nomadic Apache Indians. The old village probably contained quite as many people as the modern agency, and possibly more, for traces of pottery can be seen on both sides of the valley. The other village, which I did not visit, is said to be located about 12 miles below the agency and 5 miles above the modern village of Tularosa, which lies out in the plain at the mouth of the Tularosa Valley. Ruins are described in the plain also, but they are beyond the limits of our present investigation.

Nearly 2 miles below the agency the valley bottom is broken by one of the relatively steep slopes described above. The plain below the slope is quite flat and almost swampy. It is cultivated, however, by means of irrigation from a small spring, and with a little more care could easily be made highly productive. On either side the plain is bounded by gravel terraces, 20 or 30 feet high. At the base of the northern terrace, near the upper end of the plain, Mr. A. M. Blazer, who lives a little way up the valley, pointed out the ruins of an ancient canal. Originally it appears to have been a simple ditch, but now it is a mass of calcareous tufa about 3 feet wide, 4 feet thick, and hundreds of feet long. Its top is grooved to a depth of about a foot, and the sides of the groove have a thickness of about 6 inches. Its upper end is lost in the plain, either having been buried or eroded away. The lower end disappears under a road which runs nearly parallel to the ditch. Beyond the road it can not be detected and has probably been entirely removed by erosion. The peculiar feature of the ditch is that it was not built to water the plain. If that had been its purpose it would have been carried along the foot of the terrace. Instead of this it was carried along the face of the terrace with as little slope as possible, so that it gradually leaves the plain and approaches the top of the terrace, which, of course, has a steady slope downstream. The ditch must have been designed to irrigate the top of the terrace, which it would reach about half a mile downstream. There, as pointed out by Mr. Blazer, a tract of 400 to 500 acres could be irrigated. This land is now unused, partly because it is surrounded and somewhat dissected by gullies, and still more because after the bottom lands have been irrigated there is not enough water left to make it worth while to build a ditch to irrigate the terraces. The ditch was clearly in use for a long time, long enough at least to allow the water of the spring to deposit from 2 to 4 feet of calcareous tufa. Moreover, it was carefully engineered, with a slope as gentle as possible, and apparently with many windings. To-day the windings would almost preclude the construction of such a ditch unless masonry were employed, but in the days when it was built the tributary gullies had probably not been cut to such depth as now.

The phenomena of the old canal imply conditions different from those of to-day. Two possibilities present themselves. In the first place, the bottom lands may have been essentially the same as now, but the population was so dense that all this land was used and more was needed. Therefore an attempt was made to utilize poorer land lying on the terrace. The attempt was successful, as is evident from the thickness of the tufa, which implies long use of the canal. The amount of land in question would have made such an attempt well worth while. According to Mr. Blazer, the total amount would be about half as much as is now under cultivation in the entire valley, including all at this village and at the lower ruin, 12 miles away. The size of the canal indicates that it carried approximately the same amount of water as the present stream furnishes except in times of flood. The other hypothesis was suggested by Mr. Blazer as his only solution of a problem on which he had pondered for years. When the canal was built, so he surmises, the valley bottom, now half a mile wide, was gullied out so deeply that it could not be cultivated. Possibly an alluvial plain which had formerly been cultivated had been rapidly gullied by the same process which is now beginning to destroy the present plains. At any rate the ancient inhabitants were obliged to have recourse to the land at the top of the main terrace. Having more skill than we generally suppose, they were able to achieve the work of making the canal without tools of iron, although the difficulties due to the washing away of sections of it by the sudden floods of little tributary gullies must have been great. Which of these two hypotheses is correct can not now be determined, nor is it essential. In either case it seems probable that since man occupied the country the hydrographic conditions have changed, a conclusion which agrees with the other evidence in showing that at least the last cycle of the terrace-making process has occurred since man began to build villages and practise agriculture.

A

B

C

D

A. Ruins of little stone terraces at Rincon Canyon. The stones have here been much disturbed by occasional floods. In places where they are less disturbed, bushes hide them and make photography difficult.

B. Defensive Hohokam walls on a hilltop near San Xavier.

C. Looking down from the top of the Trincheras of the Magdalena River, showing terraced fields on the dry slope and modern irrigated fields at its base. The rectangle in the center of the terraces is the ceremonial platform described on page 68.

D. Site of an ancient village in Southern Arizona, metate and mano stones for grinding seeds in the foreground.

CHAPTER VII.

THE ANCIENT PEOPLE OF SOUTHERN ARIZONA.

We now come to far the most important type of evidence as to the relation of man to the climate of pre-Columbian days. The number of ruins in southern Arizona and northern Sonora is remarkable. I do not here refer to the well-known cliff-dwellings, nor to the ancient villages and irrigation works of the Gila Valley and its tributaries. In addition to these there are literally hundreds of villages located still farther south. Most of them have never been examined at all by scientists, and none have been adequately described. Indeed, most people who live in their immediate vicinity scarcely know of their existence. The reason is obvious. Usually the ruins are so insignificant in appearance that an unobservant traveler might ride for a mile through a village without becoming aware of the fact. (See Plate 2, D.) On the hilltops walls are sometimes found, built evidently for protection; on the slopes below the fortresses little terraces for dwelling-houses or other purposes are located. These have been duly noted by anthropologists, as have ancient pictographs in certain passes or near the fortresses. For our present purpose, however, they are of relatively slight importance. The really significant ruins are those of a great number of villages located in the plains. Their sites are now reduced to barren expanses strewn with ornamented bits of broken pottery, flint knives and arrowheads, stone hammers and axes, mano and metate stones for grinding seeds, and in some cases rectangular lines of boulders placed erect at intervals of a foot or two, and evidently outlining the walls of ancient houses. Here and there a little mound a foot or two high shows where a house was located. In almost every village an oval hollow surrounded by a low wall covers an area 100 to 200 feet long by half as wide—not a reservoir, as one at first supposes, but probably a ceremonial precinct of some sort. Aside from this nothing remains. Yet there can be no question that these were once ancient villages. In many cases the ground to a depth of 2 feet or more is thickly filled with bits of pottery, while the surface is so strewn with similar bits that one can scarcely walk without stepping upon them. The houses were probably built of branches, wattled perhaps with mud. Such houses in course of time would utterly disappear, for the wood would decay, the clay used for wattling would partly blow away, and the rest would be so small in amount that it would not be noticeable. Where a house was more thickly wattled than usual or was built of adobe low mounds now tell the tale. Other dwellings, in villages close to the mountains where stone is easily available, were strengthened at the base of the walls by upright boulders which still stand in their original position, so that one can see the exact form of house after house. The majority of the houses, however, have disappeared, and in many cases whole villages show scarcely a trace of the original dwellings. Yet they were no transitory villages. The amount of pottery shows that they must have been filled with a busy population for centuries. In certain cases, to be sure, the amount is so small as to indicate only a brief occupancy. In the larger ruins, however, the amount is literally scores of times as great as in modern Indian villages such as Cababi or Juivak, whose inhabitants still use pottery almost entirely, and which have been inhabited for at least 50 years. It is equal to the amount found in Asiatic ruins which are proved by dated records to have been inhabited for hundreds of years. The ancient villages are insignificant in appearance, not from any lack of traces of prolonged human occupancy, but merely because of the flimsy construction of the houses and the length of time since their abandonment.

ANCIENT CONDITIONS OF LIFE AMONG THE HOHOKAM.

Before proceeding to discuss the ruins in detail, one or two points of general importance need emphasis. In the first place, the builders of the villages are not known to have been allied to any tribe of modern Indians. They may possibly have been related to such folk as the Zuni or Moki tribes, but of this we have as yet no decisive proof. Probably they were at most no nearer to them than the primitive Teuton was to the modern Anglo-Saxon, or the ancient Jew to the modern fellah peasant of Palestine. To assume that because the modern Indians follow certain practises the ancient inhabitants also did so, is as fallacious as to assume that because the modern people of Palestine believe in the seclusion of women the ancient Jews did likewise—or that as the modern Persians are noted for their tendency to prevaricate, Xenophon and others were wrong in praising the ancient Persians as speakers of the truth. In so far as the habits and customs of a people are directly determined by physical environment, the ancient inhabitants of Arizona must indeed have resembled those of to-day, except in points where a change of climate, if such has occurred, would alter the prevalent mode of life. Undoubtedly Arizona has always been relatively dry and agriculture has always been dependent upon irrigation; nevertheless the poverty, famine, pestilence, war, depopulation, and other miseries which adverse changes of climate seem to occasion may have given rise to a large body of habits and customs widely different from those of earlier times. Thus under favorable climatic conditions peace may have prevailed, whereas a change of climate may have led the tribes of the driest areas to adopt predatory habits, which in turn compelled the occupiers of the better portions of the land to practise the arts of both defense and offense. Again famine and scanty nutrition due to decrease in the food supply may have fostered plagues and pestilences to such an extent that new customs arose as to the burial of the dead, or as to the abandonment of houses in which people had died. In a score of other ways the habits of the past may have been different from those of the present, even in matters directly controlled by physical environment; in other respects, such as religion, social customs, and political organization, there is still greater room for diversity.

I emphasize this point because there is a strong tendency to argue that, because the modern Indians have a certain custom, their predecessors must have done likewise 1,000 or 2,000 years ago. If it were proved beyond doubt that physical conditions were then the same as now, this would be more legitimate; but while the matter is open to question, such a method of argument is unscientific. It may, of course, be true that the people of the past were much like those of the present, but in the present state of knowledge it is wrong to use any such assumption as the basis of reasoning. To avoid the danger incident to the association of ideas with words, I shall not use the term Indians or Amerinds in connection with the ancient inhabitants, but shall call them Hohokam. "The term Hohokam, 'That which has perished,' is used by the Pimas," says Russell,* "to designate the race that occupied the pueblos that are now rounded heaps of ruins in the Salt and Gila river valleys [50 to 100 miles north of Tucson]. However ready the Pimas may have been in the past to claim relationship with the Hohokam or relate tales of the supernatural origin of the pueblos, they now frankly admit that they do not know anything about the matter." The term Hohokam, accordingly, implies nothing as to the origin or relationship of the builders of the ancient villages, and therefore may appropriately be used in a specific sense for the vanished race of southern Arizona and the neighboring arid regions.

Another point which needs emphasis is that the Hohokam were a distinctly agricultural people. The ruins are located on the edge of the lowest available gravel terrace, just above broad expanses of rich alluvial land. The only exceptions are in alluvial plains so broad

* F. Russell: The Pima Indians. 26th Ann. Rept. Bureau American Ethnology, Washington, 1908, pp. 23 and 24.

that there are no gravel terraces within a reasonable distance. In the part of southern Arizona and northern Sonora under discussion, I examined the ruins of about twenty-five villages. Not one was located primarily in a position favorable for easy defense; even when sites suitable for this purpose were close at hand they were not utilized for the main village, but only in a secondary fashion as refuges, apparently in troublesome times, perhaps toward the last days of the Hohokam. Water, also, to judge from present conditions, was not a prime factor in the choice of sites for villages. Fully half of the ruins that I examined lie from 0.51 to 8 miles from the nearest permanent spring or perennial stream. All the villages were obviously placed where it would be most easy to reach rich alluvial land capable of producing abundant crops if properly irrigated. Fewkes, Mindeleff, Hough, and other anthropologists who have written on the similar ruins farther north and east all emphasize the peaceful, agricultural character of the ancient inhabitants. The mode of life of the Hohokam, whoever they were, clearly had no resemblance to that of such warlike, hunting tribes as the modern Apaches. Agriculture was almost their sole reliance, for domestic animals other than the dog were unknown in pre-Columbian North America. Beasts of the chase were not eaten to any great extent, as appears from the scarcity of their bones in the various old pueblos and cliff-dwellings where ancient scrap-heaps have been found on the upper tributaries of the Gila and Salt rivers and elsewhere. Some bones, to be sure, are found, showing that the Hokoham had no aversion to flesh, but the number is not large. Traces of corn and beans and, to a much less extent, of wild products are found in much greater abundance, showing that the main source of livelihood was agriculture.

There is still another point on which stress should be laid at the outset. In the absence of any proof to the contrary, we shall assume that the Hohokam were in general the same as the rest of mankind. For instance, if we find ten houses of ordinary size in a village, we shall assume that ten families lived there. This may prove to be a mistake, but the burden of proof is on those who assume that ten houses represent less or more than ten families. Likewise we shall assume that the Hohokam did not leave a good location for a poor one except temporarily under stress of exceptional circumstances. The writings of anthropologists are full of assumptions directly contrary to this. For instance, Mindeleff says that "A band of 500 village-building Indians [by which he means the people whom we have called Hohokam] might leave the ruins of fifty villages in the course of a single century."* That is, he assumes a degree of mobility unparalleled among any modern agricultural or village-building people. Possibly he is right, but such an assumption can be accepted only after careful proof. Accordingly in the following pages the reader must bear in mind that, when density of population is spoken of, we refer to the density which would have existed if the Hohokam had been like other normal races in the same stage of development.

One final point deserves to be kept in mind. In comparing the capacity of the country to support population at present with its capacity in the past, allowance must be made for the fact that the ancient inhabitants were handicapped by the lack of many of the accessories which we deem most essential. Cattle-raising, the cultivation of wheat, barley, and oats, the use of iron or metal tools, the industries connected with transportation by rail, wagon, horse, donkey, or any other means except the backs of men and dogs, and finally the many activities connected with mining, were all unknown to the Hohokam. None of these things existed in the America of their day. Not only was the population entirely agricultural, but its agriculture was carried on without any facilities except stone implements, and plants such as corn and beans, indigenous to America.

* 13th Annual Report of the Bureau of Ethnology, 1891–92, p. 259.

THE FORMER POPULATION OF THE SANTA CRUZ VALLEY.

Turning now to the discussion of specific areas, it is evident that the solution of our problem depends upon the relative density of population and the amount of water available for agriculture in the past as compared with the present. We must exclude regions now well populated, for they prove nothing either one way or the other. We must also exclude regions now depopulated and full of ruins, but capable of being reoccupied. These also prove nothing: the driving out of the former inhabitants may have been due to pestilence, or to the incursion of warlike tribes, such as the Apaches; but the pestilence and the raids, in their turn, may have been the result of adverse climatic changes. Accordingly we shall pay little attention to such regions and shall confine ourselves for the present to the almost uninhabited lower part of the Santa Cruz Valley below Tucson, and to certain tributary valleys with an equally sparse population. Then, for the sake of comparison, we shall consider the Altar and Magdalena valleys in northern Sonora. These, like the Santa Cruz and its tributaries, rise near the border between Mexico and Arizona, but instead of flowing northwest for 150 miles to the Gila, they flow a similar distance to the southwest, where they unite and empty into the Gulf of California. As a matter of fact, neither the Altar-Magdalena nor the Santa Cruz sends any water to the sea except in occasional years of phenomenal floods. The permanent stream of the Santa Cruz ends near Tucson, more than 70 miles from the Gila, while the permanent stream of the Altar terminates near Caborca, about 50 miles from the Gulf. (See map, frontispiece.)

Before investigating the ruins, let us see how many people the Santa Cruz Valley is capable of supporting by agriculture at the present time. According to Professor R. H. Forbes, the records of the Arizona Experiment Station, of which he is the Director, show that the entire drainage area of the Santa Cruz, including all its tributaries, contains approximately 6,000 acres under cultivation of some sort. This includes not only areas regularly irrigated in the ordinary fashion by surface water, but also some that depend upon underground water raised by steam or gasoline pumps, and other considerable tracts which are watered merely by temporary floods and hence produce only a single crop of alfalfa per year instead of four or five, as is the case in the lands receiving more abundant water. Under the best system of irrigation available at the present time, Professor Forbes estimates that for every 2 acres brought under full cultivation one person is added to the population of Arizona. This includes merchants, artisans, and all the varieties of people needed to carry on the business of life. In other words, if the Santa Cruz Valley were cut off from the rest of the world and left to its own resources, as it was in the days of the Hohokam, the population would be limited to the number of persons who could be supported on the 6,000 acres of irrigated or partly irrigated land. To this number nothing could be added by dry farming without irrigation, for Professor Forbes expressly states that at the present time, in spite of various attempts, no such thing as genuine dry farming is carried on in the lower parts of Arizona. Experiments are in progress which may soon render it possible, but any such process was certainly far beyond the capacity of primitive people like the Hohokam. A certain number of persons might be added by the possibilities of hunting and of sustenance from wild products, such as the fruit of the cacti, the mesquite beans, and so forth. The number would be limited, however, for it is well known that a hunting population of one person to the square mile is dense even in a moist region furnishing abundant forage for herbivores and rodents. In a dry region like Arizona the number would be less. Nor could wild fruits and seeds add greatly to the density of population, for they are abundant in the years of good rainfall when the cultivated crops are also abundant, while they fail in dry years, "especially in hard times," as a Pima Indian naively remarked to Russell. In times of poor crops the Hohokam doubtless made extensive use of wild products; but this means that there could not have been any large number of people dependent upon such products alone, for if such were the case, part of the population would inevitably have starved in dry years.

At the present time the region to the west of the Santa Cruz Valley is inhabited only by Indians. They utilize what little water is to be found and carry on a little hunting. A large part of their sustenance, however, is derived from the cattle and horses introduced from Europe. Besides this they have deep wells, a convenience unknown to the Hohokam because of their lack of iron tools. Moreover, the modern Indians utilize wheat, barley, and other plants introduced by the Spaniards; and, finally, they go out in hard times to work in mines or in the towns of the white man. In spite of all the advantages which the modern Indian has over the old Hohokam, the population of the Indian region west of the Santa Cruz amounts to an average of only one per square mile, and could not be increased greatly, if at all, without the introduction of some new means of livelihood. Take away from the modern Indian his cattle, wells, wheat, and other results of the white man's presence, and the population would be cut in half. No race, whether Hohokam or Indian, could hope to exist in any but the scantiest numbers without the aid of irrigation.

Coming back once more to the amount of irrigated land and the number of people which it could support, we recall that 6,000 acres of good land under full cultivation would support approximately 3,000 people under present conditions of agriculture. Primitive methods of agriculture, however, as Professor Forbes puts it, without stock, wheat, wells, or any means of raising water by mechanical power, such as the steam pumps which run night and day on many farms, would by no means permit of one person for every two acres. Russell gives some figures (pp. 86–8) as to the amount of land cultivated by the modern Pimas. According to him each family cultivates from 1 to 5 acres of thoroughly irrigated land. On the next page, however, he says that the individual holdings of each family vary from 100 to 200 steps in width, according to the size of the family. He defines the step as 5 feet, which would make the smallest plots 6 acres in size and the largest 25, so we are left in doubt as to the actual amount under cultivation per individual. Moreover, if we knew the amount of land per individual among the Pimas, we should still know nothing as to the Hohokam, for the Pimas get at least half their living from the white man's cattle, from government grants, from work in the towns, and from many sources unknown to the Hohokam. Hence we come back to the figures of Professor Forbes. If the white man with his steam pumps for irrigation and his iron tools for digging canals and making dams can only cultivate 6,000 acres, the Hohokam could scarcely cultivate more. If the white man with his winter wheat, his knowledge of fertilizers, and his domestic animals for plowing and for utilizing hay, straw, and other materials inedible by man, can support only 3,000 people, or one for every two acres, the primitive Hohokam, even though his standard of living was lower and he was aided by game and wild fruits, could scarcely have made the same 6,000 acres support more than 4,500 people, or half as many again as the white man's limit.

Granting that 4,000 or 5,000 is a reasonable maximum limit to the number of Hohokam who could find a living in the Santa Cruz Valley under present climatic conditions, let us next see where they would be located. Inasmuch as the location of the ruins and the consensus of opinion among ethnologists prove that the Hohokam were preeminently an agricultural race, they must have lived where both land and water were available. At present about 1,500 of the 6,000 cultivable acres are at the Indian Reservation of San Xavier, 9 miles up the Santa Cruz to the south of Tucson; 600 or 700 Indians now live there, cultivating the land, raising cattle, and going out to the neighboring city to work. In the days of the Hohokam a fairly dense population lived at San Xavier, as is proved by various ruins, including a large fort on the hilltop half a mile away from the present village. (See Plate 2, B.) Around Tucson itself lies another irrigated tract embracing 2,000 or more acres. We can not tell exactly how extensive an area was here occupied by the

Hohokam, for the houses and streets of the present city cover a large area. Just outside the city, however, not only to the south nearly across the Santa Cruz from the old mission, but also to the north along the terrace near the Southern Pacific Railroad, and to the west near the Desert Laboratory and the Hospital, pottery and other evidences of early man are found in abundance, while on Tumamoc Hill above the Laboratory the walls of a fort may be seen. Evidently many Hohokam lived at Tucson and cultivated the 2,000 acres or more which are there available for irrigation. A third large tract of modern cultivation is found along the Rillito, a stream which flows at the southwestern base of the Santa Catalina Mountains and joins the Santa Cruz about 8 miles below Tucson. Here nearly 2,000 acres are now used. In the past the Hohokam evidently made use of the same land, for traces of villages are found at Agua Caliente, Tanke Verde, and in the angle between the Rillito and Pantano washes, a mile southeast of Fort Lowell. Other traces of former occupation are found along the terraces of the Rillito, so that there can be little question that every available bit of land was cultivated.

The three areas mentioned above, namely, the San Xavier Reservation, the vicinity of Tucson, and the Rillito Valley, are the only places where water is now abundant. They include about 5,500 of the total 6,000 acres available for cultivation. The remaining 500, more or less, are scattered here and there in small insignificant patches. Thousands of acres of most fertile soil lie along the lower Santa Cruz below Tucson and in many other places, but can not be cultivated for lack of water.

Let us examine some of the ruins in the region where cultivation is now largely or wholly lacking. Seven miles northwest of Tucson the little railroad section house of Jaynes lies on the edge of the alluvial flats on the northeast side of the alluvial plain of the Santa Cruz. From a point a mile southeast of the station, that is, toward Tucson, pottery and stone implements are strewn thickly not merely as far as Jaynes, but for nearly half a mile beyond. These evidences of an ancient village lie upon a gravelly tract which now rises perhaps 10 feet above the main alluvial plain. The width is only about a quarter of a mile in most places, for the village was evidently spread out along the length of the stream. Everywhere the pottery is so thick that one walks on it at almost every step. The area where pottery is thick amounts to at least 200 acres, while, downstream, potsherds are less abundantly strewn for about 2 miles to a point beyond the Nine Mile Water Hole, near the mouth of the Rillito. In most places the traces of the ancient village are limited to the southwest side of the railroad toward the Santa Cruz. Close to Jaynes, however, they cross over and spread out upon a higher terrace. Here they cover the gravel "mesa," as the bahadas are locally called, and may be seen in abundance along the direct road from Tucson to Rillito just west of the Flowing Wells Ranch, the lowest point to which a perennial water supply now comes. This portion of the Jaynes village occupied the triangular point between the Santa Cruz and Rillito bottom lands and had an area of at least another hundred acres, while in the outskirts scattered fragments indicate a less dense population, extending far on every side. In this village and in the adjacent main area of the Jaynes ruins the pottery is so thick and extends to such a depth in the ground that we can scarcely doubt that the villages were densely populated for a long time.

The number of people contained in the original villages can not be estimated with any exactitude. An approximation may be made from comparison with the ruins at Sabino Canyon, a tributary of the Rillito. Where the Sabino brook flows southward out of the Santa Catalina Mountains it has deposited a broad fan of gravel, in which it has now cut a wide flood-plain bordered by a terrace. On the gravel terrace east of the stream, a Hohokam village was located. To-day the only inhabitants of the immediate vicinity are two or three Mexican ranchers who use all the available water to irrigate a score or more acres of bottom land. In the past the village appears to have been quite populous. In the triangle between Sabino and Bear Canyon "Washes" an area of 35 acres is covered with the foundations of houses, while a surrounding area of the same size is strewn with pottery, but less thickly than the main area. The Hohokam of Sabino, being close to the mountains, employed stones to strengthen the foundations of many of their houses. The outlines can still be seen with perfect distinctness, rectangles of boulders 1.5 to 2 feet in long diameter set up on end a foot or two apart. My companion (Mr. Bovee) and I counted 62 houses in the 35 acres of the central area, and there may have been others concealed by gravel washed down from the mountains. Moreover, part of the old houses may have had no stone foundations. At any rate the village certainly contained at least 62 houses of various sizes scattered at intervals of 100 or 200 feet over an area of 35 acres. The houses vary in size. Many small ones, located as a rule on the outskirts of the village, are only about 15 by 20 feet in dimensions and are often divided into two rooms. The ones nearer the center of the village are larger, and one inclosure has a size of 250 feet by 110; another of almost equal size appears to have been a temple; it is divided into several rooms surrounding a courtyard, in the midst of which is located a circular pavement about 15 feet in diameter. Judging by the number of houses, the amount of pottery, and the presence of a temple or other large public structure, this was no temporary village, but was inhabited permanently. The inhabitants must have been cultivators of the soil, for their village is carefully placed where the stream comes out of the mountains and the arable land begins. Across Bear Canyon Wash a minor village or suburb still shows the ruins of six houses. Apparently at least 68 families lived here, which would mean at least 250 people. Their support would require 500 acres of land, according to the estimates of Professor Forbes. There is apparently sufficient land in the vicinity, but only a small part of it can now be watered. The villagers can scarcely have used the lands or the water farther down the valley or in other neighboring valleys, for each of these has its own ruins.

Leaving the matter of water supply, let us attempt to form some idea of the number of people who lived in the old Jaynes village. The pottery at Sabino is by no means so abundant as at Jaynes, indicating that the population was less dense. It also seems to extend to a less depth in the ground, suggesting a less long occupation; yet there is enough to indicate an occupation of centuries, if comparison with modern Indian villages is any guide. However this may be, it seems clear that the great double village near Jaynes was more thickly populated than Sabino. If the 300 or more acres, which were densely strewn with pottery, were covered with houses placed no more closely than those of Sabino, that is, at average intervals of 140 feet, the total number must have been at least 500, without taking account of the large number which clearly existed in the surrounding, less densely populated areas. This would mean at least 2,000 people in the main town and certainly 500 in the suburbs. These 2,500 would need at least 5,000 acres of irrigable land, according to the best authority on modern agriculture in Arizona. In other words, we have seen that in the vicinity of the sites where agriculture is now most feasible something like 5,500 acres of land are in use. Ruins indicate that all of this was cultivated in the days of the Hohokam, and common sense tells us that no sane man would leave the easily watered land uncultivated and betake himself to land with a precarious water-supply. Nevertheless, in the region just below the Tucson area of cultivation the Hohokam established a great village which must have demanded almost as much land as the entire amount now in cultivation. All the land available for their use was in a district below, that is, downstream from the last extensive area which now is capable of profitable cultivation. Its case is exactly like that of the Sabino ruins. Both appear to have been permanent agricultural villages, but both demand an amount of irrigable land far in excess of that now available.

Ruins of the Jaynes type are numerous. One of the most important is located at the so-called "Point of the Tucson Mountains," or Charco del Yuma, as the Mexicans call it, a mile or more south of Rillito Station on the Southern Pacific Railroad. The name is commonly abbreviated to Charco Yuma, and has sometimes been incorrectly printed as

Shakayuma. Here, below the mouth of the Rillito Wash, the broad, waste-filled basin of the combined Rillito and Santa Cruz streams contracts to a narrow neck. On the south the volcanic range of the Tucson Mountains projects into the plain, while about 2 miles to the north the rocky foothills of the granite range of the Tortillitas rise from the alluvial gravel. A buried dam of rock, so to speak, here crosses the Santa Cruz Valley beneath the cover of alluvial deposits, causing the level of underground water to be relatively high upstream from the point of the mountains, while downstream it rapidly falls. In the spring of 1910 we found that the source of surface water nearest to Charco Yuma was 8 miles up the Santa Cruz at the Nine Mile Water Hole; there the amount was sufficient for drinking purposes, but not for any appreciable irrigation. Ranchers engaged in raising cattle informed us that no water whatever had come down the river during the preceding winter, although during the summer of 1909, when the rainfall amounted to almost exactly the average quantity of 7 inches, floods came down after 15 to 20 showers. In some cases the flow continued only 2 hours; in the height of the rainy season, however, a brook of greater or less size flowed steadily for 2 weeks. The average duration of the floods was about 36 hours. From this we infer that, during a summer of average rainfall, surface water flows as far as Charco Yuma for about 30 days, during July or August. Socoro Ruelas, a Mexican who in boyhood and early manhood lived at the old stage station, one of the cattle ranches at the Point of the Mountains, states that in winter water seldom flows there. Even the heavy showers of summer sometimes fail to send any stream so far down the valley. The nearest permanent source of water, as has been said, is at the Nine Mile Water Hole, 8 miles away, but even this, he says, sometimes dries up, although at other times (such as the late seventies or early eighties) water flows 2 or 3 miles from it and has actually been used for irrigation. From the spring of 1885 to August 1887, according to the Mexican, no water whatever came down as far as the Point of the Mountains. In 1884, when Ruelas's father dug his well, water was struck at a depth of 28 feet; during the following dry years the level fell below this, but water never absolutely failed. In the winter of 1909–10 the level was 22 feet. I can not vouch for the dates here given, but there can be no question as to the general accuracy of the facts.

A talk with Mr. Langhorn, the station-master at Rillito, a mile or more north of the old stage station and the Hohokam village, seems at first sight to put quite a different aspect on the matter. Here a narrow strip of cultivated land extends along the railroad for more than 3 miles. "Talk about dry farming," said Mr. Langhorn, "it's the easiest sort of thing. Five inches of rain a year is all we need here. Just look at my fields. They're not so good as usual, but they show what can be done even in a bad year like this. It's all in the way you plow and harrow and roll." A little investigation, however, soon shows that the 300 acres here cultivated are provided with very effective irrigation, not artificial, but natural. Because of the raising of the level of ground water in this particular spot by the contraction of the valley, the moisture is nearer to the surface than elsewhere. When floods come down, water accumulates in pools. Mr. Langhorn pointed out patches in which the barley was then particularly fine, but which can not be planted in some years because of the moisture. Even in bad seasons these fields are much wetter than any other place for many miles. The winter of 1909–10 was by no means propitious. Although the rainfall amounted to only a little less than the average, it was badly distributed, most of it falling early in the winter. Accordingly the grain planted in September and October, and even in early November, grew fairly well, while that planted after the middle of November failed to head. Even in the best part of the 300 acres available for cultivation in this district, the hay crop, for which the barley is planted, was expected to amount to only about 15 tons, although in the preceding year it had been 95. This particular area has not been cultivated long, and its possibilities in really dry seasons have not been tested. At least a quarter and possibly a third of the winters in the last 43 years have been even more unpropitious that was 1909–10. If a rainfall of 2.88 inches in that year could cause the diminution of the crop to the extent of five-sixths, it requires no demonstration to show that the fields must have been almost useless in the 9 years, since 1867, when the winter rainfall has been less than that amount. Many attempts have been made to cultivate areas outside the 300 acres now in use, but have met with no success. Of course in years like 1904–05, with nearly 15 inches of winter rain and 6 in the summer, or 1906–07, with nearly 8 in the winter and 11 in the summer, fine crops can be raised in a great many places; but this is the exception, not the rule.

To sum up the conditions at Charco Yuma as set forth by the two men quoted above and by others, it appears that no permanent supply of water is available without the digging of wells at least 25 feet deep. The nearest permanent supply of surface water is 8 miles away. A period of two full years may elapse without a single temporary flow of water. The total amount of land capable of cultivation amounts to about 300 acres, or enough for 150 people, but this yields very variable crops, falling off as much as 85 per cent, even in years which are by no means the worst. We are almost certain that the ancient Hohokam knew nothing of wells, for not only have none ever been described among their ruins, but the total absence of iron implements would render the digging of deep wells practically impossible. Moreover, the Hohokam had no winter crops of any importance, for the indigenous grains and food plants of America do not lend themselves to winter growth. Hence the ancient inhabitants were limited to the products of the summer rains. Now, according to Ruelas, no flood water reached Charco Yuma in 1885, when the summer rain amounted to 3.01 inches, the minimum on record, nor in 1886, when it amounted to 4.27. We may safely say that if *no* water reached the place with a fall of 4.27 inches, crops of any appreciable value could scarcely be raised with less than 5 inches. During the 45 years for which records are available, 15 summers, or one-third, have had a rainfall of less than 5 inches. Hence we seem compelled to conclude that under Hohokam methods of agriculture the total amount of land now available for cultivation amounts to only 300 acres, which would yield no appreciable crop at least one year out of three.

The Hohokam lived in this vicinity in large numbers. In the fields around Rillito Station, according to Mr. Langhorn, the plow frequently turns up bits of pottery or stone implements from beneath 5 or 6 inches of fine silt deposited by recent floods of the Santa Cruz. Half-way from the station to the Point of the Mountains a gravelly tract of older alluvium in the midst of the silty areas of later deposition is also well strewn with pottery. These evidences of the presence of the Hohokam suggest a somewhat numerous population scattered wherever alluvial land occurs. No special stress, however, should be laid upon these facts. They are unimportant compared with the phenomena of Charco Yuma proper.

Where the Tucson Mountains jut their last spur forward toward the north, the sandy bed of the dry Santa Cruz runs nearly westward at the base of a series of rugged black hills, rising from 300 to 500 feet above the plain. East of the hills, in the narrow strip of plain between their base and the river-bed, Mr. Herbert Brown, editor of the Tucson *Star*, showed us the remains of a large village. For nearly 2 miles we found pottery and other artifacts scattered along the base of the mountains, not thick as a rule, but at frequent intervals, as if houses had been located here and there along the edge of the cultivated land, just as they seem to have been along the Cañada del Oro and other dry stream-beds, or as the houses of the modern Indians are to-day at San Xavier. In the center of the village the pottery is thicker. Here we found a great boulder of andesitic lava almost buried in alluvium, and studded with 24 round holes about 10 inches deep and 3 inches in diameter. A similar block not far away contains 7 holes of the same sort. Long ago the Hohokam women must have gathered here with their stone pestles, and gossiped as they sat on the great rocks and pounded the corn, beans, or other seeds to make flour for the daily bread of their primitive husbands and sons. Not far away an elliptical inclosure, 210 by 90 feet in size, is surrounded by thick mud walls which, in spite of being much broken down, still present the appearance of a ridge 4 or 5 feet high. The interior was evidently hollowed out to a level slightly below that of the surrounding plain, while the walls of dry mud must have had a height of not less than 6 or 8 feet. Similar inclosures are found in many ruins, for instance at Jaynes on the upper terrace, where several lie close to the road on the south side just east of where it descends to the lower level on which the railway station is located. Hasty examination suggests that these are reservoirs, but a little study shows that usually they are so located that water could not possibly be caused to flow into them and fill them. Their walls rise so far above the level of the plain that even if canals, of which there is no sign, carried water to them, only the lower portion, to a depth of 2 or 3 feet, could be filled. Moreover, some of them have broad entrances not appropriate to reservoirs. Structures of the same sort are found in all parts of the drainage area of the upper Salt and Gila rivers, and go far toward proving community of race or at least of civilization among all the inhabitants. Mindeleff and others have come to the conclusion that these were ceremonial chambers, roofed, perhaps, with branches supported upon poles. This seems highly probable. If the theory is correct the presence of such temples would in itself indicate the existence of villages of considerable size and permanency.

Back of the temple and the great grinding stones, if these terms are allowable, the whole eastern and northern face of the hills is covered with low walls, 2 or 3 feet high, protecting the exposed side of roughly smoothed spaces from 10 to 30 feet wide. Apparently these were built as places of refuge for the inhabitants of the village below. Each one may have been covered with a booth of branches, although there is no direct evidence of this. The Hohokam certainly spent a good deal of time here, for pottery is scattered thickly. Probably the potsherds represent largely the broken fragments of jars in which water was brought from below, although where the water came from is a puzzle. If the oval hollows are temples, no sign of reservoirs has been detected anywhere on the plains, nor has any trace of cisterns been noted on the hillsides. The number of platforms or inclosures is great. At first one is tempted to say there must be a thousand of them. We did not count, but a rough estimate shows that they surely number several hundred. No distinctly defensive walls are found here, like those at Tumamoc Hill near Tucson or on the mesa at San Xavier. Possibly this site was abandoned before the pressure of hostile tribes had led to the development of the art of defense to the point where regular forts were constructed. At any rate, the hill was apparently a refuge for the inhabitants of the village on the plain, and the number of platforms agrees with the size of the area where pottery is found in indicating a population numbered by hundreds of families.

On the west side of the hills forming the Point of the Tucson Mountains another large village is found. For a distance of nearly 1.5 miles along the terrace above the alluvial plain of the Santa Cruz, pottery and the usual accompanying artifacts are thickly scattered. The central portion of the village occupies an area of about 200 acres, while the surrounding part, where the population was less dense, covers a slightly larger additional area. In the center of the village pottery is very thick and the upper layers of earth are full of it to a depth of 2 feet. In the portion where pottery is thickest, not far from the foot of the hills on the east and from the terrace leading down to the river on the north, lines of stones indicate the foundations of houses, as at Sabino. We did not count them, not realizing at the time how important they might be. It almost seems as if they represented an occupation later than that of the rest of the village, but this is mere conjecture. The decorations on the pottery and the occurrence of inclosures such as those which we have taken to be temples prove that in general the people here were like those in the other villages of this region. The hills on this side rise as steeply as on the other and offer as good a shelter from enemies, but they seem to be devoid of refuges or walled inclosures like those on the opposite side. If Charco Yuma West of the Mountains had existed at the same time as Charco Yuma East of the Mountains, the same necessity for protection must have existed in both cases. Hence it seems probable that the western and larger village was abandoned in favor of the eastern at a time when protection against enemies had not yet become a vital necessity. The western village is more favorably located than is the eastern with respect to agricultural lands, such as those of Rillito or the rest of the Santa Cruz Plain, but it is not so sheltered as the other, nor so near to the river bed, whence water was presumably derived. If a progressive diminution of the water-supply had anything to do with the matter, the supply of the lower village would fail before that of the other; for the village east of the mountains is located where the level of permanent underground water is at a depth of a little over 20 feet, and a slight rise would bring it within reach of the surface; while in the bed of the river adjacent to the western village the ground-water level is at a depth of 50 feet or more. The greater abundance of pottery in the western village, the greater depth to which it is buried, the greater degree of weathering of the wall of the temple inclosure, and the absence of all defensive structures on the hills suggest that the western village dates from an early time, presumably of peace and prosperity, while the eastern village dates from a later period of greater stress and danger. If the same line of reasoning is pursued farther, we may infer that the absence of a genuine fort at Charco Yuma and the presence of such structures at Tucson and San Xavier indicate that in course of time conditions grew still worse, so that the outlying town at the Point of the Mountains was abandoned, while the upper towns began to seek the protection of regular forts. The abandonment of the lower town may have been due to desiccation and the consequent failure of the crops, or to the growth of warlike tendencies among the neighboring peoples.

In offering these suggestions we are venturing upon the realm of theory rather than of proven fact. The justification for this lies in the fact that among Asiatic ruins of similar character, in the deserts of Chinese Turkestan and elsewhere, written records prove that the villages were abandoned one after another, beginning far downstream and progressing upward. Further comment on Charco Yuma is unnecessary. Its population was apparently almost as great as that of Jaynes; it was inhabited for a long time, and its people must have required much water both for drinking purposes and for the irrigation of fields. The supply available in the vicinity to-day is limited to floods in wet seasons and is often entirely lacking for many months, sometimes for over 2 years at a stretch. No trace of reservoirs has been found, and no reservoir which could be built in this flat, dry region could retain water more than 5 or 6 months, as is proved by modern experience in more favored localities. The arable land is limited to 300 acres, and even this small tract often fails to produce a good crop.

Seven miles below Charco Yuma, or 24 miles down the Santa Cruz from Tucson, Mr. W. J. Wakefield showed us a small ruin located about 0.7 mile due north of Nelson's Desert Ranch. It is over 3 miles from the dry bed of the Santa Cruz, and 3 miles from the lower end of the strip of arable land which begins at Rillito Station. The level of ground water is so low that in digging a well at the ranch it was necessary to go down 182 feet. This is stated on the authority of Mr. Wakefield, who lived here as a boy and whose knowledge of this region and others, both in Arizona and Mexico, was most kindly put at our disposal at much inconvenience to himself. At the ruins near Nelson's Ranch the water-level must be still lower than at the ranch. A few small "washes" lead occasional floods down from the Tortollitas Mountains some miles to the north, but there is absolutely no hint of any permanent water-supply. The ruins consist of a rectangular inclosure, 210 by 175 feet, with the long side running N. 25 E. magnetic, or N. 37 E. true. A wall of earth, now almost obliterated, surrounded the inclosure and was pierced at the southern corner by a gateway. In the opposite, or northern, corner a mound or platform 65 by 50 feet in size rises 8 or 10 feet. Nothing like this was found in any other ruin which I saw in either Arizona or Mexico. The pottery also was unusual. The majority was of the common type, terra-cotta with brown lines forming triangles, feathers, or other patterns. Certain pieces, however, were of large size, bright red in color, with black designs. These looked comparatively fresh, as if of late date, but the appearance may have been deceptive. Other pieces were pinkish-purple in tint with designs in white lines, or else dark brown with purple designs. These, to one who knows nothing of pottery, appear to be older than the ordinary, more commonplace ware. Some of them were ornamented on both sides, a practise not noticed elsewhere. Certainly the shape of the ruins separates them from others in this part of Arizona, and the unusual variety of design and color in the pottery and its uncommonly fine texture suggest a higher artistic development than is found elsewhere. Also the site is more absolutely waterless than any other yet discovered. Whether all these things indicate great age and early abandonment I do not know. The village was never large. Outside the rectangular inclosure pottery extends thickly for only 600 feet, although scattered bits are found for half a mile. The village was apparently agricultural, although no cultivation is now possible in its vicinity.

The list of ruins in the lower Santa Cruz Valley is not yet complete. Over 50 miles from Tucson, in township 8 S., Range 7 E., near the corner of sections 20, 21, and 28, Mr. J. B. Wright, irrigation engineer of the Santa Cruz Reservoir Company, showed us another old ruin, about 3 miles southeast by east of Santa Cruz post-office, west of Toltec Station. Some day the extensive projects of the reservoir company may possibly bring this region under irrigation, but in 1910 no water had been secured in spite of a large expenditure of money on a dam and canals, and the next year the company gave up its work. To-day the ruins are still miles away from any region where agriculture is possible and from any source of water, either for irrigation or drinking. The center of the village is marked by an elliptical inclosure of the usual type, which could not possibly have been a reservoir, as it stands too high. Pottery extends to a distance of 500 to 600 feet about it. Twelve miles south of Toltec Station, in an equally waterless district at the northern base of the Sawtooth Mountains, the reservoir company in 1910 erected a large dam, now abandoned, which was designed ultimately to be about 40 feet high, and to hold in reserve a supposedly large body of flood water which, however, failed absolutely to materialize in 1910. At the eastern end of the dam we rode three-fourths of a mile through ancient pottery. At the western end, a mile away, the traces of a large village can be seen. During the progress of the work on the dam various objects were brought to light, such as an image of a man, another of a pregnant woman, a stone phallus, and some pieces of slate, very smooth, and covered with carvings said to suggest hieroglyphics. These are now in the possession of Colonel Green, of Cananea, Mexico. In other portions of the now desert plain of the lower Santa Cruz, far below the limits of any but the largest floods, the workmen came upon numerous traces of old villages. In one case, about 3 miles southwest of Toltec Station, or half-way from Santa Cruz post-office to the station, Mr. Wright came across a drainage line which runs nearly east and west *across*, instead of with, the line of steepest slope. Such a channel could scarcely be formed by nature, and hence Mr. Wright thinks that it may be an ancient canal, possibly the continuation of the one which presumably led to the ruin described at the beginning of this paragraph. It is still possible that the construction of huge irrigation works such as those projected by the Santa Cruz Reservoir Company, with dams miles in length and reservoirs covering whole townships, may gather sufficient flood water to cause the region once more to be populated, but no traces of the existence of any such thing in the past have ever been found. In the Salt and Gila valleys, to be sure, old canals are frequently noted, but nothing at all comparable to the works which would here be required. Hence there is scarcely the remotest possibility that they ever existed. Without them the only means of sustenance in all the region from Rillito downward is the hunting of jack-rabbits or the keeping of cattle watered from deep wells. In one or two places a few acres can at times be cultivated when the floods come down strongly, but any reliance upon agriculture is out of the question. At best the population is limited to a few cattle ranches miles apart. Yet in the past it was dotted with numerous agricultural villages.

Before leaving the Santa Cruz drainage area we must describe two more sites located close to the mountains and affording phenomena different from anything yet discussed. The first is at Gibbon's Ranch, a mile or two east of Sabino Canyon, at the southern base of the Santa Catalina Mountains. The peculiarity of this site is that it is one of the few where the water-supply depends upon a spring rather than a stream. At present the site is unoccupied. A decaying adobe house stands beside a small reservoir supplied by two or three trickling little springs. The total amount of water at the time of our visit in March 1910 would scarcely suffice to irrigate 3 or 4 acres. Just what its capacity is can not be stated, but at any rate the owner of the ranch did not find it worth while to practise agriculture, and turned his attention entirely to cattle raising. Since his death or removal, no one has lived there. Some day, perhaps, some thrifty Chinese peasants will establish here a little market garden. They will certainly be most skilful if they can make the water suffice for the support of much more than two or three families. East of the spring a dry wash occasionally carries floods from the mountains. Close beyond it lies the site of an old village of the same type as the one at Sabino Canyon. Mr. Bovee and I counted the foundations of 28 houses in an area of 8 acres. The entire village, that is, the district strewn with pottery, amounts to almost 40 acres. Apparently the trickling springs, which are not now deemed worth using, once supported more than a hundred people.

At Gibbon's Ranch, as in other ruins, a structure which appears to have been a temple lies in the heart of the village. Although in an extreme state of ruin, it appears to have been elliptical in shape. The main northern wall, which is the best preserved, is about 105 feet long and is oriented east and west magnetic or N. 78° W. This brings up an interesting fact: In all the villages where stone foundations occur there seems to be a more or less definite scheme of orientation, which is closely adhered to in the temples and larger buildings, and is less and less closely observed as the structures decrease in size or are located at a greater distance from the temple. I measured the orientation of 55 foundations in 7 different villages located in four widely separated localities. They were distributed as follows:

Group I. Sabino, 37 measurements; Bear Canyon, 3; Gibbon's Ranch, 3.
Group II. Rincon Valley near Sentinel Butte, 2; 1.5 miles from Sentinel Butte, 8.
Group III. Empire Ranch, 1.
Group IV. The Great Trinchera of the Magdalena Valley in Sonora, 1.

Out of the 55 structures, only 8, 5 of which are in the main village in the Rincon Valley, diverge more than 10° from east and west magnetic. Even including these the *average* direction of all the walls is within a third of a degree of east and west, or north and south, according to the present direction of the compass, which here points about 12° east of north. The explanation of this orientation possibly lies in some astronomical phenomenon. The ancient Aztecs observed one of the chief feasts of the year early in May at about the time when the summer rains begin in the City of Mexico. Possibly the Hohokam observed a similar festival. At any rate, early in May and again about the first of August the sun sets approximately in the direction of the main walls of the temples and houses of the Hohokam.

The study of the ruins of the main Santa Cruz Valley and some of its tributaries led to the conclusion that a mere examination of the map was sufficient to indicate where ruins would be found. Accordingly I decided upon the head of the Rincon Valley, about 22 miles southeast of Tucson, as a test case. The expected ruins were found in the shape of vestiges of several small villages, the chief of which contains the foundations of at least 18 houses. There can not have been less than 25 houses in this small mountain valley, and quite possibly more, for pottery is scattered thickly far beyond the limits of the foundations. The present population consists of two American and two Mexican families. One of the Americans is the forest ranger; the Mexicans are vaqueros, or cattle-men. The other American is the only man who does much farming. He says that the cultivated land amounts to 200 acres, but his individual figures total only 150, and even this seems in excess of the visible fields. Granting that the figures are correct, however, the arable land with the water supplied by the brook might suffice for a population such as that indicated by the ruins. Therefore nothing can be argued either for or against changes of climate. Certain other phenomena, however, bear directly upon the subject. About 1.5 miles east of the forest ranger's house and about 3 miles east by north of the prominent hill called Sentinel Butte, a grassy slope drops toward the northwest at the base of Rincon Peak, 8,465 feet high. The slope has a fall of about 10°, and an altitude of from 3,300 to 3,500 feet above sea-level. On the smoothest part of it, for a distance of about half a mile parallel to the upper Rincon and for a width of about one-half or two-thirds as much, one finds unmistakable terraces built apparently for purposes of agriculture. In general they are from 20 to 70 feet long and 2 or 3 feet high. The commonest location is at right angles to the minor drainage lines, each little swale being broken into terraces with a width of from 20 to 30 feet, as appears in Plate 2, A. In some cases the spaces between the swales are also terraced. The terrace walls are all composed of pebbles and cobbles. I searched carefully for pottery, but succeeded in finding only one or two coarse bits, quite in contrast to the abundant potsherds which occur not only among the foundations lower down in the valley, but all along the borders of the alluvial plain. The only other works of man among the terraces are some small stone circles resembling modern mescal beds, where the agave is cooked, and a round structure 7 feet in diameter. The whole hillside closely resembles hundreds in Palestine, Syria, and Asia Minor, or in Mexico and South America. Even the little round structure with its small doorway resembles the watchmen's shelters in the terraced fields of Syria. There can scarcely be any doubt that the terraces were designed for agriculture. Apparently they were not intended for irrigation, for they are not properly arranged, nor does there appear to be any available source of water. They must have been intended for dry farming. Near the main village, down in the valley 3 or 4 miles away, the gravel slope just east of the gully which bounds the village on that side is interrupted by a few similar terraces. Apparently dry farming was attempted in more than one place.

As has already been said, Professor Forbes, of the Arizona Experiment Station, states that dry farming is not now practicable in Arizona except by means of most careful and expensive methods of plowing and harrowing. The terraced slope in the upper Rincon Valley, because of its proximity to the mountains, undoubtedly receives more rain than do many parts of the country. Over on the east side of the Santa Rita Mountains, at an elevation considerably greater than that of our terraces, potatoes are said to be cultivated without irrigation, but further inquiry shows that they are watered naturally by springs bursting out above them. In the same region, at the mouth of Gardner's Canyon, at an elevation of about 5,000 feet, four or five settlers took up land and attempted real dry farming in 1909. The elevation is sufficient to insure moderately cool weather much of the year and hence less evaporation than in the parching plains. The rainfall in the summer of 1909, as measured at the Empire Ranch not far away, amounted to 9.39 inches as against an average of 7.93 for the preceding 15 years. Nevertheless the corn failed entirely; and the beans, the most reliable of all crops, gave so scanty a return that the farmers were completely discouraged. In the absence of records of rainfall, we can not say categorically that crops might not be raised on the terraces at Rincon. We can merely say that nothing of the kind has succeeded in this part of Arizona hitherto, and that in April 1910 we found the terraces with no more sign of fresh vegetation than was apparent on the surrounding dry plains.

The hypothesis may be advanced that the Hohokam here cultivated some special crop, such as wild tobacco or some native plant now unknown, a plant for which dry conditions are especially favorable. No such plant is now known, according to Dr. MacDougal and the other botanists of Tucson. The space covered by the terraces is so large that we can scarcely assume that such a crop would be of sufficient importance to require so great an expenditure of effort. Moreover, so far as is known, no plant after having once, so to speak, been made a part of man's equipment, has ever escaped from cultivation; accordingly we must pass by this assumption as one for which there is no ground. The cultivation of products such as grapes or fruits would demand irrigation or greater rainfall.

Apart from the immediate question of the possible climatic significance of the terraces, they are important in another aspect. Mankind rarely labors except under strong compulsion, whether of hunger, desire, fear, ambition, or love. The ancient Hohokam would scarcely have gone to the labor of making the terraces without some good motive. The obvious agricultural character of the structures precludes the idea of any religious significance, as does the fact that elsewhere such terraces are found closely associated with religious structures from which they are clearly different. The only adequate cause for the terraces would seem to be the need of more abundant areas of cultivation or the desire for luxuries such as grapes. Defense apparently had nothing to do with the matter, for there seems to be no fortress near at hand, and the terraces are not in a particularly defensible position, in fact quite the contrary, being at the foot of a mountain side. Accordingly, it seems most probable that the Hohokam of the Rincon Valley found that the land at their disposal was not sufficient for their needs. Therefore, having somehow learned the art of making terraces as practised in other parts of the arid southwest or in Mexico, they built a considerable number, partly close to their main village, but chiefly on a slope of especially favorable location. This in itself may seem of small importance, but it is significant as indicating that probably the population was decidedly dense. Had there been an abundance of unused irrigable land either in the Rincon valley or in the neighboring regions, the Hohokam would scarcely have gone to the labor of building terraces.

RUINS IN THE DESERT REGION WEST OF TUCSON.

Further description of the ruins of the Santa Cruz Valley would add no new types, although it would show more conclusively the surprising number of the ancient villages. Accordingly we shall now turn to other regions in order to indicate how widespread are evidences of an apparently numerous population in the distant past. About 60 miles southwest by west of Tucson, the little Indian oasis of Artesa stands in the midst of an area of thousands of square miles inhabited only by Indians. Nowhere in the whole region is there a perennial brook, and even springs are of the utmost rarity. The white man does not live here, because there is nothing for him to desire. Here and there he has made attempts at mining, but with such poor success that in practically every case work has been abandoned. Even the Indians find life no easy matter. One or two thousand of them cluster here and there in little villages, depending for part of the year upon the water of broad, shallow reservoirs filled by the floods, but compelled in the dry seasons to resort to the mountain valleys and drink from wells dug by the white man's art. As they sit by their smoky fires of desert bushes they talk of the years of drought. In 1903 and 1904, if my Indian informant had the dates correctly, no rain of any value fell from the end of the winter showers in March of the first year to the beginning of the rains of the second winter, 18 months later, in October or November of the succeeding year. The Indians obtained no crops whatever; they killed or sold some of their cattle, got credit at the stores, or went off to work in the mines. They would have starved without the resources furnished by the white man; they would have perished of thirst, had they been forced to stay in the region without his deeply sunken wells, the work of tools of iron. We can scarcely emphasize too strongly the dire straits to which the Indians would to-day be driven if dependent only upon their own primitive resources. Even in the well-watered Santa Cruz Valley the struggle for subsistence would be hard enough, but in the drier regions farther west it would be far worse.

In spite of the inhospitable character of the country west of Tucson, it once was much more densely populated than now; at least, it is full of ruins. I shall not attempt to describe the small ones in the immediate vicinity of Artesa, nor shall I dwell on those described by various persons, including Americans, Mexicans, and Indians, but which I have not seen. A few lying off to the northwest of Artesa will serve to illustrate all. Beginning at a point about 4 miles northwest of Artesa, a line of volcanic buttes extends northward with plains on either side. Floods flow past them from the low mountains of Comovavi* to the northeast, but there is no long-continuing source of water until Nolik is reached, 11 miles from Artesa. Even there the water is not derived from springs or brooks, but from a deep well. Nevertheless, the buttes are covered with defensive walls and with little inclosures like those on the hills above the villages of the Santa Cruz. On the first butte we saw from 50 to 100 of the little, rudely walled platforms, wherein we have inferred that families took refuge in time of danger. Down below on the south side of the butte we found pottery scattered about, not thickly, but in such quantities that it could only have been left there by long occupation of the site. How many other villages and forts there may be is unknown. We saw defensive walls on two buttes, and a prosperous Indian at Nolik informed us that they are found on many others.

Thirty miles to the northwest of Artesa the modern village of Covered Wells, the home of the Papago chief, spreads its scattered houses here and there along the sides of a valley in the Quijotoa Mountains, about 65 miles west of Tucson. As usual the site of the modern village does not at all resemble that of the villages of the past. It is determined by the location of one or two wells. Close to the modern houses no sign of ruins is apparent, for the Hohokam, unlike the modern Indians, deemed good land as necessary as good water. Six miles east of the upper part of Covered Wells, however, and 4 miles from the lower village, on the way toward Tucson, an Indian youth showed us the ruins of Maisk, or "Hidden," as the name was interpreted by the guide. They lie far out from the mountains, beyond the limit of stones and gravel, where the soil is fine and fertile, and where the floods from the mountains can spread abroad and water the plain. Just at this point the road runs nearly parallel to a dry "wash" which sometimes brings down a considerable quantity of flood water. At present no attempt at cultivation is made here, although farther down the wash, where the floods finally spread into a thin, playa-like sheet and soak slowly into the ground, the Indians from the villages beside the wells at the base of the mountains live for a time, and sow their seed. Nevertheless, for three-quarters of a mile at Maisk the wash, which lies just south of the road, is flanked by an area thickly strewn with pottery, which spreads to a distance of nearly 1,000 feet on either side. In one place my companion, Mr. Godfrey Sykes, of the Desert Botanical Laboratory, found a straight channel which looked as if it might have been an irrigation ditch. In another he found what seemed to be the dam of a simple little reservoir 3 or 4 feet deep. Such a shallow reservoir can not have remained full for many months, for one 15 feet deep at the mountain village of Comovavi lasts only six or seven months, so rapid is the process of

* Often written Comobabi, properly Com Vahia.

evaporation. If the houses at Maisk were on an average 100 yards apart, the number must have been 80 or 90. If they were grouped like those at modern Cababi (properly Covavi) or at the ancient village of Sabino, the number would have been nearly 450; or if like those at the ruins near Gibbon's Ranch, 600 or more.

The ruins of A'ai Sto, or "White on Both Sides," as our guide translated it, lie some 3 miles southwest of Maisk and are of the same type in all respects. They lie along the sides of the wash which comes down from Quijotoa post-office, and are situated just below the point where the wash crosses the road from the Covered Wells to the old pump-house of the abandoned Logan Mine. I walked in the pottery-strewn area for 2,000 feet and had not come to the end of it. Slight mounds at the upper end, here as at Maisk, suggest the remnants of the more important houses, made perhaps of adobe plastered upon a wooden frame, or even made into walls by itself. The Indians know nothing of the ruins save that they have always been just as they are to-day. They can not explain why they were located here where now there is neither water to drink nor land sufficiently watered for cultivation. When I asked where the ancient villages got their water, our guide from Jiuwak, as the lower part of Covered Wells is called, replied that he did not know. The elders of his village, so he said, were of the opinion that the Hohokam brought water from a spring up in the mountains a little south of Quijotoa post-office. The spring lies 3 or 4 miles from Maisk and 2 or 3 from A'ai Sto, and 1,000 or more feet above either. That this should have been the main source of water for two large villages is incredible. To be sure, the women of Comovavi carry water a mile or more from a well located some 400 or 500 feet higher than the village; but this is less than half the distance required at the ancient villages. Moreover, the modern village is located as near to the well as is convenient, which is not the case with the ruins in respect to the spring, and, finally, Comovavi gets its water for seven or eight months from reservoirs. The depth of these, as already mentioned, enables them to hold water much longer than could possibly be the case with such shallow reservoirs as could be constructed at the ruins.

CHAPTER VIII.

RUINS IN NORTHERN SONORA AND SOUTHERN NEW MEXICO.

Before attempting further to explain the facts presented in the preceding chapter, let us consider the ruins of northern Mexico. The little town of Altar (ältär′), 132 miles southwest of Tucson as measured by automobile, is the metropolis of the dry northwestern corner of Mexico. So long has this site been inhabited that the soil contains a surprising abundance of pottery. The flat adobe roofs of some of the houses are so full of it that one walks on it as on a pavement. Twenty-two miles farther to the southwest the last inhabited place of any size on the Altar River is reached at Caborca. Here, too, indications of ancient occupation abound, and the hills on both sides of the town show a few little walled inclosures for defense. From this point to the Gulf of California there is no village properly speaking, although the distance is over 50 miles. Our visit to the Altar Valley was made at the suggestion of Dr. MacDougal, who had heard and read enough of it to feel sure that it would be a good region in which to test the conclusions reached along the Santa Cruz. After the upper parts of the valley had been seen under the competent guidance of Mr. H. Harrison, of Caborca, a trip was made down the river to the sea in order to test our conclusions. At Cerro Tortuga, near the so-called "Port" of Lobos on the uninhabited shore of the Gulf, we had seen a remarkable group of ancient graves of wholly unknown origin. In the immediate valley of the lower Altar, however, we could hear of no ruins aside from those of a Spanish Mission at Buzani, about 14 miles southwest of Caborca. Except for two or three Mexican cattle ranches, the great plain extending thence for 40 miles to the sea is an uninhabited desert. It seemed likely, nevertheless, that if the climate was formerly more propitious than now, the region once contained villages. Accordingly we drove down the dry river to the Gulf of California.

At Buzani, in the midst of the monotonous expanse of the modern alluvial flood-plain, we found one Mexican and five or six Papago families living with their cattle beside a well about 200 feet deep. They were raising the water in great leather buckets, drawn by horses. The poor beasts had no collars, but were forced to pull with the whole dead weight of the bucket attached to the pommels of their tightly girthed saddles. In good years several hundred acres can be cultivated here, but in 1910 we found that nothing had been planted, because of the lack of winter rain. Half a mile to the north, on the low gravelly terrace bounding the silty plain, the old mission church stands in the midst of the ruins of a village. Inside the church little wooden images mark the graves of newly departed Papagos, while an offering of a few cigarettes shows that the modern Indian is still a pagan. Outside the ruined mud edifice pottery, sea-shells, and metate stones of lava cover a space of 30 to 40 acres. Immediately around the church numerous heaps still mark the sites of fallen houses; some are almost obliterated and only the church, being well built of adobe bricks, stands firmly. Doubtless the houses date back little more than a century. The pottery is not the old sort with brown ornaments painted upon it, but consists of coarse, unadorned modern varieties, intermingled with a few bits of cheap ware with a green or yellow glaze. We counted 18 mounds close to the mission, and estimated the number of dwellings in the adjacent area of recent occupation to be from 40 to 60. Except in one respect, these ruins have no special significance. Doubtless in part they date back to very early times, but the last occupation, in the time of the Mission, can scarcely go back more than 150 years. This leads us to query, "Why was the Mission ever established here where there is so little water? Missions are usually located in the best places in the country, where villages still prosper. Here, on the contrary, a permanent village was impossible before the days of wells. At most the Indians could only live here for a few months during the flood season; their permanent village must have been elsewhere. Why, then, should so substantial a mission have been established? Also why is there no well close to it, but only a canal which is dry most of the year? The only answer seems to be that probably in the latter half of the eighteenth century, when the Spanish fathers came this way, a longer or shorter period of abundant precipitation had produced a supply of water somewhat greater than exists at present. We are far from saying that this indicates a change of climate in so short a time as a century and a half; yet it seems to suggest that fluctuations of fairly long period are now in progress, and that in the eighteenth century the country was blessed with a period when the rainfall for a while was somewhat more abundant than during the average seasons of the last three or four score years.

Below Buzani no agriculture is carried on to-day: the floods are too uncertain to make it worth while for any one to attempt to rely on farming, although one or two cattle-ranchers plant a little grain if water happens to be abundant. Nevertheless, about 10 miles below Buzani, above the ranch of Alamo San Francisco, we discovered a ruin of the regulation type. The natives apparently knew nothing of it, but by searching along the terrace corresponding to the one where most of the ruins are situated, we found it. For over a mile it stretches east and west beside the dry stream-bed, while the width, as usual, is only about a third of the length. Practically the whole of this large area is thickly covered with artifacts, chiefly pottery of the same type as in the Santa Cruz ruins, but with a few new patterns. Shells of clams and other animals also abound, indicating proximity to the sea. Another notable feature is numerous patches of hard clay about 3 feet in diameter. They are burned to a red color to a depth of from 4 to 6 inches and appear to be fire-places. Judging by modern fire-places, such a depth of burning must indicate prolonged or constant use. Besides these there are numerous other round beds of small cobbles, which may also be fire-places. Often these are in ruins and charcoal is mingled with the stones. The number of inhabitants may have been considerable. The area of the village is greater than that of modern Caborca, whose population, according to Mr. Harrison, may be conservatively estimated at about 1,500. The number of fire-places and the thickness of the pottery sufficiently indicate a dense population. If the houses were as near together as at the little village of Sabino near Tucson, which, it will be remembered, was less densely peopled than most of the ruins, the number of families was probably at least 400.

Another old town, San Francisco, is found 4 or 5 miles below Alamo San Francisco, and still farther from any visible source of water. Its essential features are like those of the neighboring ruin, save that no clay fire-places were noted, only those of cobble-stones. This ruin is smaller than the other, only about 2,000 feet long, and the pottery is not so thickly strewn.

Below San Francisco we found no pottery or evidences of ancient occupation for about 25 miles. Possibly ruins exist and were missed because we followed the sandy wagon trail and could not inspect the edge of the terrace for miles at a time. Finally, at Disemboque, near the mouth of the river, pottery appears once more. How great an area it covers is not certain, but it is widely spread. A little more than a mile from the sea the dry channel of the Altar breaks through a ridge of sand-dunes 15 to 20 feet high, which apparently mark the line of an old strand located 5 or 10 feet above the present level of the Gulf of California. At places the old strand and that of to-day come close together, but usually they are distinct. Possibly there has not been an actual change in the level of the sea, but merely a building out of a delta by the river. At any rate, when the Hohokam dwelt here, the seashore seems to have been farther inland than now. Habitations were built close to it, as is proved by the great abundance of pottery. Here, if one may judge from the heaps of shells, the people gathered to feast on clams, oysters, and half a dozen other kinds of shell-fish. At first one surmises that there may have been no real village, for the Hohokam may merely have come to the shore to gather shell-fish, but this is not the case. Undoubtedly the shell-fish were an important item in the food supply of the ancient people. Often they gathered one special variety, such as razor clams, and perhaps ate it exclusively, leaving other kinds for other feasts, as appears from the character of the shell-heaps. Back from the shore, however, signs of an agricultural village are visible in the form of pottery scattered thickly for a distance of a mile or more. Shells, on the other hand, are no more abundant than in the villages many miles in the interior, which would scarcely be the case if the Hohokam had come here merely to get food from the sea. The pottery is found chiefly on slightly elevated tracts 5 to 15 feet above the general level. Apparently some sort of erosion, presumably eolian, has carried away much of the soil, leaving hollows, which have since been partially filled by deposition from the floods of the river. Possibly this condition existed when the Hohokam lived here; they may have built their houses on the high places and cultivated the low ones. One thing at least is clear: many people lived here whose interest was apparently not in being close to the sea, but in being close to land which then was presumably arable and now would be highly productive if only it were supplied with water.

Taken as a whole the conditions of the lower Altar are like those of the lower Santa Cruz. According to tradition, the whole plain of the lower Altar was once under cultivation by the Papagos or their predecessors. The tradition, however, as related by the Mexicans, is not at all definite, and may have no foundation other than observation of the phenomena which have been described above. No one who carefully examines the region can fail to be impressed by the abundance of ruins, the care with which they are so located as to command the best agricultural land, and the hopelessness of now attempting, by means of primitive methods of cultivation, to support even a handful of families in the regions where the Hohokam once seem to have been numerous.

Phenomena which may have a bearing on the question of changes of climate are found not only below, but above the present lower limit of cultivation in the valleys of the Altar and its tributaries. Chief among these are the so-called trincheras or terraced hills. One such is said to be located near Altar, but that which will here be described lies farther to the south in the Magdalena Valley. From Altar it is reached by a ride of 14 miles southward to the Magdalena River, and then southeast up the river for 21 miles. Much of the way the road leads through a beautiful country, which would deceive the uninitiated into the belief that it is the best of farm land. The fine, fertile soil is well covered with short, thick grass, which in early May 1910 had been dry and brown since the end of the rains of the previous summer. Even in better seasons than 1909–10 the rain does not last long enough to enable crops to be raised without irrigation, except in the very best years.

The Trinchera is a dark rugged hill rising 600 feet above the smooth plain, while smaller hills flank it to the east and southwest. The slopes of all the hills are divided into innumerable terraces, the work of an ancient people. To the north the broad alluvial plain of the Magdalena is covered with fields of waving wheat, or with brown patches, left unsown for lack of water for irrigation. Not far from the base of the hills lie the mud houses and square corrals of a Mexican village, while the brush shanties of an Indian hamlet are located a little farther away. (See Plate 2, c.)

Long ago a branch of the Hohokam lived here. In some respects they differed from their northern brethren in Arizona, but not essentially. Among the sparsely scattered bits of pottery which we found, we noted none painted with the ordinary brown designs. The only decorated piece, picked up by Mr. Harrison, was adorned with a rectangular pattern of red, blue, and black, and was more complex than anything that we saw elsewhere. The Hohokam of the Trincheras used metates and manos for grinding corn and beans, just as did their neighbors 100 to 200 miles to the north. They likewise constructed temples oriented with the long walls pointing toward the place where the sun sets in May. Yet they differed from the people of southern Arizona in that they were more skilled in the arts of wall-building, defense, and agriculture.

The Great Trinchera is of special interest because it appears to combine three types of structures, religious, military, and agricultural. Possibly traces of houses may also be visible, but we detected none. The hill is somewhat crescent-shaped, about 1,800 feet long from point to point of the crest, and lying with the concave side facing almost due north toward the distant river. Beginning at the base of the steep slope on the north side, about 20 terraces rise one above another. Some are 5 feet high, and some 15; some 10 feet wide, and others 20 or 30. Below these main terraces the ground slopes more gently than above. Just where the slope changes, and in the center of the concavity of the hill, the Hohokam built what seems to have been a temple or, better, a ceremonial platform, an almost rectangular structure with a length of about 165 feet and a width, from north to south, of 30 feet at one end and 40 at the other, a shape appropriate to a narrow terrace. Rude walls of boulders piled up without cement surround the platform, and are pierced by a door at the western end; while in the center of the north side a circular inclosure, 12 feet in diameter, with a door to the south, appears to have been the holy place. From all points of view the ceremonial platform stands out prominently, because it is the only place from which all the stones have been carefully cleared. Its character is here emphasized, because it seems so plainly to be a religious or ceremonial structure, and as such is strongly differentiated from all other structures on the hill. The portion of its walls composed of stone was probably never more than 4 or 5 feet high, for, with the poor materials at their command, the Hohokam apparently could not build much higher without mortar to bind the stones or tools to square them. The gentle slope below the temple is broken into terraces like those on the steep slopes above, except that they are only 1 or 2 feet high and 20 to 50 feet wide in accordance with the angle of descent. We shall discuss their purpose later.

In early days the Hohokam of the Trinchera may perhaps have been as unwarlike as those of Charco Yuma, but they certainly lived to learn the art of defense. The crest or ridge of the hill is strongly fortified. Nine successive walls surround the main hilltop at the western end. On the central part of the ridge, above the concavity in which lies the temple, the Hohokam built a fort, breast-high, with walls 6 feet thick and with a circular bastion projecting from it on the exposed south side. Here and there on the terraces little, low, circular inclosures, like those among the Rincon terraces, may have been of service as outposts. Just how the Hohokam fought we do not know, but Mr. Harrison found a collection of small cobble-stones 1.5 to 2 inches in diameter, just the right size to throw. Evidently they were brought up the hill for some special purpose, which can scarcely have been anything but defense.

We now come to the question of the purpose of the terraces. Obviously they are not for religious purposes, for the one religious structure is clearly differentiated from them. They are equally differentiated from the military portion of the structures on the hill. None of them are protected by walls, and the lower ones (a foot or two high) would render practically no defensive aid whatever. Are they for habitation? According to local tradition the Trinchera is a species of Tower of Babel. When *the* flood, or possibly *a* flood, overwhelmed the country, the Hohokam took refuge on the hills and made for themselves dwelling-places. There is no reason, however, to suppose that the terraces were ever inhabited except temporarily. In the first place, pottery is too scarce to justify such a supposition; in the second place, the shape is not adapted to habitation, for some of the terraces are so narrow that there is scarcely room even for a tiny hut, and many terraces taper to a point in a way wholly unsuited to houses. Finally, the whole aspect of the terraces strongly suggests that their purpose, like that of the ones at Rincon, is for agriculture. The terraces of the Trinchera closely resemble those built for agricultural purposes on innumerable hillsides in all parts of Asia and in some of the other continents, and the resemblance is so close that strong evidence would be required to prove that the purpose in one case was different from that in the other. Two facts tend to confirm this conclusion. In the first place the terraces are almost lacking on the hot, sunny south side. This does not pertain to the whole south side, but only to the portions which have a steep slope and would consequently be dry. Secondly, the terraces extend as far as the slope continues, and then merge smoothly into unquestionable agricultural land. On the west, north, and east the land is even now capable of cultivation, and could be irrigated if the Mexicans chose to use it rather than to employ the better land actually in use. On the south the hillside ends in a genuine bahada, whose lower portion is of gentle slope and of fairly good soil, although full of boulders and gravel. When walking across this one notices nothing special unless his attention has first been called to it, but when viewed from above, the land is seen to be neatly divided into rectangles, presumably fields, about 40 feet wide and 100 or more long in the direction of the slope. So distinct are these that they can be clearly seen in photographs. Inasmuch as the rectangles can be detected only from an eminence, it is possible that many more exist elsewhere undiscovered. Russell* describes what appear to be similar old fields far to the north, beyond the Gila River. Taking account of all the facts, it seems as if both the terraces and the rectangles were designed for agriculture. If this were so, dry farming must have been practicable then, although now it is out of the question. Here, as at Rincon, the Hohokam may have desired to increase the area of cultivation because of growth of population, or they may have desired to cultivate special products, such as grapes. Possibly, also, they may merely have wished to have a certain amount of land immediately under the shelter of their fort, so that at least a small crop might be safe in times of invasion. This last supposition is somewhat doubtful, however, for the neighboring little hills, one of them at least half a mile away, are also terraced, but have no defensive works.

One further possibility suggests itself: Did the Hohokam women carry water up on the hillsides and irrigate the terraces in times of drought? The estimates of our party as to the amount of land available for cultivation on and around the main hill in the terraces and rectangles varied from 150 to 350 acres. Including also the other hills the total amount can scarcely be less than 200 acres, none of which could possibly be watered by any means except the actual pumping or carrying of water. Of course the Hohokam would have had to carry it, and, judging by other primitive races, the women would have done the work. The fields lie at all elevations up to 400 feet above the plain, and at various distances up to nearly a mile from where canals could be located. It is hardly to be expected that a woman should make a round trip aggregating on an average about half or three-quarters of a mile, carry her olla, or water jar, all that distance, climb at least 100 feet, pour out the water carefully around each hill of beans or stalk of corn, gossip with her neighbors, and get back to the canal or river in less than an hour. Suppose also that each woman worked 10 hours a day, which she could scarcely do in conjunction with her other tasks of grinding flour and cooking bread; and finally suppose that in three weeks' time the ground was to receive the equivalent of half an inch of rain, or in other words that each square foot received 1.25 quarts. The ordinary load for a woman is 4 gallons. Therefore 16 women would have to work 10 hours a day for 3 weeks to water a single acre. This means that in order to keep the land around the hill watered in a dry season over 3,000 women would have to be at work 10 hours a day. Counting the women who could not work for various reasons, or who were otherwise engaged, it appears that the number of women old enough to work would have had to be toward 5,000, which means a total population of

* Frank Russell: The Pima Indians. 26th Ann. Rep. Am. Bureau of Ethnology, Washington, 1908, pp. 87–88.

perhaps 15,000, where now there are scarcely more than 200. Rather than accept the supposition of artificial irrigation, we may well believe it probable that dry farming was actually possible.

The case of the Trinchera is not like that of Rincon in one respect. There the terraced area receives more rain than the surrounding areas, because of its location at the base of high mountains. Here the Trinchera lies out in the midst of a plain, far from the mountains. Moreover, the mountains, when reached, are not of great elevation. Hence the terraces and the old rectangular fields receive no more rain than the rest of the country. If dry farming was practicable there, it was practicable elsewhere. In that case we ought to find old fields in other places, that is, in the neighborhood of all the chief centers of ancient population. According to report, trincheras are abundant all over northwestern Mexico, although they do not appear to have been examined closely. Many may be so ruined that they have escaped notice. On the upper Magdelena, at a place known as Terenate, I found such an one by accident. Climbing a high hill to get the view, I was surprised to find a rude defensive wall on its top, and fallen terraces on the sides. The terraces were so broken as to be almost unrecognizable had it not been for their resemblance to those of the Great Trinchera. Being roughly constructed without mortar, and being probably of great age, they have fallen badly to ruins, but one can still readily find places where stone has been piled upon stone by human hands, forming terraces of precisely the kind described above. How many other such sites exist no one can tell; already enough have been discovered to indicate that, granting that the terraces were designed for agriculture, dry farming must have been practised on a small scale over a wide area where it is now out of the question.

Thus far we have considered the ruins in the desert region near Tucson in southern Arizona, and to the southwest and south of that town across the border in northern Mexico. Let us now consider the region lying at an equal or greater distance to the east of Tucson in southern New Mexico. So far as the ruins are concerned no new types are found, and the description of those in the Santa Cruz Valley applies almost unchanged to those in southern New Mexico Nevertheless it is worth while to present some of the details in order to bring out more fully the wide extent and large number of the phenomena upon which we may rely in our study of the past as compared with the present. Before taking up the ruins, however, it may be well to lay at rest an archeological ghost which finds shelter in various reputable publications.

The Animas "dam," or "levee," lies chiefly in the extreme southwestern corner of New Mexico, but projects a short distance across the border into Mexico. It has been described as a huge dam made to hold water for irrigation, or as a great dike upon the top of which water was carried in a semicircular course across the head of the Animas Valley. In the midst of the broad, flat plain forming the bottom of the valley it rises in the form of a great embankment varying in height from 15 to 50 feet. From the foot of the Lang Mountains on the south side in Mexico it sweeps around in a great curve, broken for a quarter of a mile on the southwest, where the Cloverdale drainage breaks through it, and then continues unbroken until, after a course of about 16 miles, it swings around to the mountains once more and then merges in a bluff which continues to the other end of the supposed dam. To build such a structure would, by actual computation, require the work of 1,000 men for 50 to 100 years. The physiographer, however, needs no such computation to prove that the "dam" is not of human origin. It presents the characteristic features of a lacustrine strand, much exaggerated, however, but still unmistakable. At some past time, presumably during the glacial period, a lake must have stood here, and must have been swept by winds of unusual severity, forming beaches of exceptional dimensions.

The actual number of people who at any time lived in the entire Animas Valley probably never exceeded 1,000, although that is decidedly more than live there to-day. Ruins of two small villages are located near the dry lake. One village, a mere hamlet, lay on the east shore at the top of the highest and sandiest part of the beach. Apparently the reason for its location in this place was that sandy soil holds the moisture better than dry, and hence is good for agriculture. The ruins of the other village lie on Cloverdale Creek, about 2 miles west of the old shoreline. In general they are like those already described, but the pottery is different and the houses appear to have contained a greater proportion of adobe and less wood or branches than those farther west. Moreover, the people do not seem to have lived in individual houses, but in small communal dwellings, as was the almost universal practise farther north. The village covered an area about 150 or 200 feet north and south by 400 east and west. The abundant but highly fragmentary pottery is mostly of a red variety with incised lines or dots. A little is yellow with black lines of ornamentation, or else red with black or brown designs upon it. Much of it has been carefully polished. The number of separate buildings is not certain, but seems to have been from 8 to 10. Each one probably contained several families, and the largest may have housed as many as 10. To-day the possibilities of agriculture, according to the one settler who lives near at hand, are most meager. During the three winters preceding our visit in the spring of 1911 there had been no running water. The summers, however, had been better, since only one during the past seven had been absolutely without water. Generally a flowing stream comes down about four times each summer. From 200 to 250 acres of land are considered capable of cultivation, but during many years no corn whatever is grown, only a little milo maize and sugar-cane for fodder, and a few beans for human consumption. The universal opinion among the inhabitants of this region seems to be that no one can live here without animals of some sort as his main reliance. The owner of a pig ranch, with whom we spent a night in the center of the old lake-bed, expressed himself forcibly to the effect that if it had not been for his pigs he would have been starved out and forced to leave the country. "If a man had to rely on what he could raise to eat, lots of years he couldn't raise it. Last year I got no rain, and didn't even raise a mess of beans."

Even the animals suffer severely. The year 1891 is said to have been the worst in recent times, but 1892 was also bad, as was 1910, while in 1904 the wells in all parts went dry or merely gave a seep of water insufficient to water cattle. Thousands of cattle died. The "Diamond A" ranch lost 15,000 out of 40,000 to 50,000 animals, and also failed to rear any of the calves, which usually number about 12,000. The animals died in large numbers around all the watering-places, and the cowboys spent much of their time in fastening ropes to dead animals and dragging them away from the water. Even the hardy antelope among the mountains suffered just as did the cattle, and died in the same way around the watering-places.

In addition to the two ancient villages already mentioned there appear to have been four others in the entire plain of the Animas Valley, which extends 40 miles northward from the old strand to the railroad. There were also a considerable number of cliff and cave dwellings in the mountains. The habitations in the mountains are said to be near spots which have water in good years, although many of them are absolutely dry for periods of over a year at a time. The largest villages of the Hohokam in this vicinity were located nearly 30 miles from the old lake near the present post-office of Animas. Here, at three different sites, fire-places and pottery are found scattered among old mounds, covered in many cases with sacaton grass. Formerly stone foundations were visible, but the score or more of settlers who have lately brought their families hither have carried them away. The number of inhabitants must have been considerable, for one of the settlers stated that he once hauled away a load of 50 metate stones to use in lining a well, and his neighbors have done likewise. The Hohokam, here as elsewhere, were a distinctly agricultural people; their number, if the ruins are a safe guide, must have much exceeded that of the present settlers. The present settlers agree with the pig-rancher already quoted. One, who has lived in the country 27 years, said that during that time only 6 years had been moist enough so that a crop of corn could be raised without artificial irrigation by water pumped from wells in the spring. A bean-crop might have been made oftener, but not over half the time. The natural flood irrigation, which supports the sturdy sacaton grass and makes cattle-raising feasible, does not usually reach the main valley until mid-July, too late for crops. Kaffir corn and milo maize do better than Indian corn, but they are of little use except for stock, and they were unknown to the Hohokam.

Two other cases, far to the northeast of the Animas region, may be briefly described as final illustrations of the Hohokam villages. The Jarilla Mountains are an insignificant group of detached hills lying in the center of southern New Mexico, 50 miles north-northeast of El Paso and 300 miles east of Tucson. Because of the presence of copper and other metals, a small mining industry grew up here a few years ago, but its boom is over and only a few hopeful prospectors still remain. As no water could be obtained among the mountains the El Paso and Southwestern Railroad, now a part of the Rock Island system, had previously been forced to construct a pipe-line to some higher mountains, 20 miles to the east. Except during the rainy season, when water is stored in cisterns, the water thus brought has formed the sole supply, not only for the railroad itself but for two little mining towns, so long as they had any inhabitants. So far as I could learn, only two persons, both of whom combine a little cattle-raising with the enticing but unremunerative occupation of prospecting, depend on any other water-supply. These two men live far off from the rest of mankind, and get their water from deep wells whose construction would be utterly beyond the capacity of primitive people without iron tools. The only surface water is in Water Canyon, but the name is a misnomer. The settler who lives there was most scornful when he was asked about the "spring." He said there was no spring, only a damp spot in years of unusually good rainfall. A visit to the place confirmed his statement. Nothing was to be seen but a waterless valley, slightly damp because rain had fallen the day before; but no one would ever suspect the presence of a spring except from the traces of an old path and of an Indian encampment. In spite of the present absolutely uninhabitable character of the Jarilla Mountains for any people not able to dig wells or construct large cisterns lined with mortar, and in spite of the fact that in ordinary years no crops can now be raised there without irrigation, one finds the remains of three distinct villages of the kind already described. The pottery and other relics of man are not so thick as in the large villages of the Santa Cruz, but they are so abundant that the ground is thickly strewn with them. No one of the villages is less than half an hour's walk from the dry spring, and two of them are 4 or 5 miles away. All are obviously located close to land which could be cultivated by flood irrigation if there were enough water and if the inhabitants could have a permanent supply to drink.

The last illustration which I shall put forth in the present connection is located on the lonely western side of the Otero Basin, not far from the western shore of one of the saline playas, whence the gypsum of the White Sands is collected by the wind. Here, in a distance of 30 miles and perhaps much more, the only inhabited place in 1911 was Beard's Ranch, where a sadly diminished stock of cattle is still cared for. Four and a half miles north of the ranch two good-sized canyons, named Dead Man and Lost Man, emerge from the San Andreas Mountains and together form a great fan of gravel and other alluvium. At the lower edge of this the traces of a large village are found. The ancient village covered an area about half a mile in diameter, thickly inhabited in the middle, and with a gradually decreasing number of houses toward the edges. In two distinct central areas pottery is so thickly strewn that one crushes it at every step; in places it is literally so thick that it is almost impossible to put one's foot down without touching it. Much of the pottery is ordinary coarse red ware, but there is a great deal that is ornamented. The greater part of that which is ornamented is painted white on the inside and is decorated with black lines. It resembles that found in the cliff dwellings and other villages farther to the north rather than that of the villages in southern Arizona. Old hearths of cobble-stones set in circles 2 feet in diameter are common, and in the center of the village are only 50 to 100 feet apart, which seems to imply a dense population. Many large stones are scattered here and there in groups among the houses, but are not now in any definite arrangement except in one case, where they form part of a circle 10 feet in diameter. Many of the stones have been broken to small bits by the action of the frost, which would seem to imply great age. The same implication is derived from the high degree to which the pottery has been broken to small fragments, and also, perhaps, from the way in which eolian erosion has scoured the ground into hollows 2 feet or more in depth.

The present water-supply at this place is almost negative, and the possibilities of agriculture are still smaller. In 1909, according to the men who live at the Beard Ranch, no water at all flowed past this place. In 1910 a little came down two or three times for an hour or two during the heavy summer rains. Even in years of good rainfall it comes only two to four times, and never for more than an hour or two at any one time. The slope here is fairly pronounced, and the soil is gravelly and porous, so that reservoirs could only be made with great difficulty. That they could hold water for two years, as would have been necessary from the summer of 1908 to that of 1910, seems scarcely possible. The nearest supply of water at any time of year except during showers is at Hughes Spring, 4 miles away among the mountains. Even if the inhabitants could have drunk from this, they could not have used it to water their crops. Indeed it is impossible to see how they could have raised crops of any kind or in even the smallest quantity under the present conditions. To-day not only do the settlers, both Americans and Mexicans, make no attempt whatever at cultivation without irrigation, but many of the cattlemen have been obliged to move away for lack of rain.

As to the age of this ruin and others, there is little direct evidence. At the Beard village a large mesquite bush, with roots as thick as a man's thigh, has grown up in the very midst of an old stone hearth. The bush, according to Dr. Forrest Shreve, of the Desert Botanical Laboratory, may be from 300 to 600 years old. Probably an equal or much longer time must have elapsed after the abandonment of the village before a seed could take root and grow in such a disadvantageous spot. These are the roughest estimates, and merely serve to show that the minimum age of the ruins is probably well toward 1,000 years, while they may be much older.

In the preceding pages a great number of facts which were observed in Arizona, Sonora, and southern New Mexico have been omitted, not because they are not conclusive, but because they are of the same type as those here included. I have endeavored to state the facts fairly without warping them to suit any particular theories. It remains for the reader to form his own conclusions as to whether they do or do not indicate a change of climate. In considering this matter it must be remembered that, for the moment, the choice is merely between the occurrence or non-occurrence of changes; the question of dates and periodicity does not enter into the matter. So far as probability is concerned, neither theory has any innate advantage. On the one side may be put the fact that the records of the past hundred years are interpreted by meteorologists to mean that there has been no change during that period. On the other hand stands the fact that since the culmination of the glacial period, presumably about 30,000 years ago, tremendous changes are universally agreed to have taken place. During the last century the slight changes which have taken place from decade to decade have sufficed to produce important effects upon agriculture, and to drive out settlers from dry regions, after tempting them in during wet times. This, however, has been on a scale far smaller than that which is applicable to the ruins. If we accept the hypothesis of no change, we must adopt the assumption that the Hohokam possessed a degree of mobility vastly in excess of that of any other known people of similar agricultural habits. We must also believe that whereas, during the past 200 years, the modern Zunis, who are often quoted in this connection, have abandoned two villages, one of which is now being reoccupied, the Hohokam abandoned their villages by the hundred without assignable cause. We must further assume that all the apparent indications of a formerly dense population are utterly misleading. The Hohokam lived here to-day and there to-morrow. Somehow they knew when the rains would be propitious: therefore they abandoned the sites where water is always abundant, and went far out into the wastes to sites which have water only in the most favorable years and where agriculture is now remunerative only about one year in five.

If we accept the alternative theory, no assumptions are required. The Hohokam acted like other races; they lived where there was an opportunity to obtain food by agriculture. When the rainfall diminished they starved, or else were driven out by enemies who themselves were set in motion by hunger. In the early times, when rainfall was abundant, they dwelt in peace and comfort; when evil days cut down the supply of water and of food, war and misery sprang up. The dwellers in the villages of less favorable location were driven into hunger and despair, and took to plundering, robbing, and raiding. Thus of necessity the art of defense was greatly stimulated among those who dwelt in the more desirable regions; and we find the best forts not in the regions at the lower ends of the rivers, but far upstream, where the dwindling Hohokam made their final stand. We might go on to show in a score of ways how one theory demands large assumptions, while the other demands none whatever. The weight of probability seems to lie on the side of changes in climate. We shall go on to see how and when these changes may have occurred.

CHAPTER IX.

THE SUCCESSIVE STAGES OF CULTURE IN NORTHERN NEW MEXICO.

The ruins of southern Arizona and the neighboring parts of New Mexico and Sonora by no means exhaust the evidence bearing on changes of climate. It is advisable to present further evidence for several reasons. In the first place the examination of numerous ruins in the northern half of New Mexico on the one hand, and in Central America and the southern part of old Mexico on the other, shows how widely the phenomena of climatic change appear to extend. In the second place such an examination brings out the fact that civilizations of quite diverse types were similarly affected. Moreover, it suggests that the rise and fall of civilization in America have been marked by a periodic or pulsatory character similar to that of the Old World and perhaps connected in some way with variations in climate. And finally, in the case of Yucatan, it brings out something of the probable nature of the changes with which we have to deal. In the present chapter I shall discuss some of the ruins of the northern half of New Mexico, leaving those of old Mexico and Central America for later consideration. Three regions will be taken up, not because they are more remarkable than many others, but because those particular ones happened to be suggested as likely to prove good places for study, and because they admirably illustrate the various stages of culture in the northern part of the area where relatively high civilization prevailed in early America. One of the regions is the Chaco Canyon on the edge of the Navajo Reservation in the northwest corner of New Mexico; another is the Pajaritan Plateau in the northern part of the State, a little northwest of Sante Fe; the third is the district of Gran Quivira, in the center of the State, south of Willard.

Chaco Canyon, which lies 85 miles from the northern or Colorado boundary of New Mexico, and 75 miles from the western boundary toward Arizona, is situated in the center of one of the most interesting regions in North America. Its bare, bright-colored mesas, wooded mountain tops, broad desert plateaus, and steep-sided, inaccessible canyons have a unique and striking quality which impresses itself upon the memory. It is surrounded by the most noteworthy ruins to be found in any part of the United States. To the north, for instance, at a distance of 115 miles, the famous Cliff Dwellings of Mancos never fail to arouse the enthusiasm of the visitor, even though he be wholly ignorant of archeology. Only 65 miles west of Chaco Canyon the innumerable ruins of the Canyon de Chelly speak of a past full of busy life and activity and characterized by a considerable degree of inventiveness and no mean amount of accomplishment in view of the opportunities. On the other side, eastward, the whole country is full of ruins, some of which will be discussed when we come to speak of the Pajaritan Plateau, 100 miles away.

The present inhabitants of the district surrounding the Chaco Canyon are no less interesting than the scenery and the ruins. To the southwest, at a distance of 80 miles, the modern Zunis are one of the few ancient tribes which still dwell in the land and perhaps preserve some connection between the past civilization and that of the present. At Oraibi, 130 miles to the west, the Hopi tribe is perhaps even more interesting as a diminished remnant of a state of culture wholly different from that prevalent in most parts of the Southwest at the time of the arrival of the Spaniards. Toward the east and southeast, at distances of 100 miles more or less, the Pueblo Indians are a third type of ancient people, less archaic than the others, but vastly different from anything elsewhere in the United

States. Surrounded by these three tribes the Navajos live in the country near Chaco Canyon, not dwelling in villages because the country is too dry to permit agriculture, nor yet plundering after the manner of their fathers because of the restraining hand of the white man, but caring for sheep and living a life almost identical with that of the nomads in Persia or similar parts of Asia.

Chaco Canyon may be reached either by wagon from Gallup on the Santa Fe Railroad or by a shorter horseback ride of 55 miles straight north from the station of Thoreau. On the way from Thoreau one passes through five distinct groups of ruins, including those at the destination. How great the actual number of ruins may be I can not say, for I could not procure a guide and was obliged to ride alone, turning aside only where I had been especially informed of the existence of something worth seeing. Nevertheless I saw literally scores of one size or another. Of modern places of habitation, on the contrary, I did not see over twenty, although I went by one road and returned by another. One of the places of habitation was a newly established Indian agency; three were the homes of white men whose sole business is trading with the Indians; two were the ranches of white men who trade with the Indians and also raise sheep in one case and cattle in the other; the rest were the temporary tents of nomadic Navajos, who camp here and there with their sheep.

Let us turn now to a description of the ruins seen on the ride from Thoreau to Chaco Canyon. Thoreau, with its saloon, hotel, store, and one or two dwelling-houses, is a typical little railroad station in the lofty plateau region of northwestern New Mexico and northern Arizona. Lying at an altitude of nearly 7,000 feet, and exposed to the unclouded rays of the sun at all times of the year, it is warm by day even in winter, and cool by night even in midsummer. The wooded Zuni Mountains rise a few miles to the south, and support a lumber industry which is the chief excuse for Thoreau's existence. On the other side, northward, the plain is bordered by a line of magnificent red cliffs which rise 1,000 feet more or less, and run for miles parallel to the railroad. Riding eastward at the foot of these one traverses a barren plain without vestige of modern habitation. No water is to be found here for many miles except along the railroad where wells have been dug. Even there it is so brackish that the few people who live at each station prefer to buy water brought by train rather than to drink that of the wells. If it were not for the railroad no one would live in the country except a few nomadic Navajos, wandering hither and thither with their sheep, according to where scanty grass or a little water are to be found. In spite of its proximity to the railroad, this is one of the most sparsely inhabited regions in the whole United States. Yet as soon as one approaches the base of the great red cliffs pottery begins to appear strewn thickly in small patches among low mounds which are evidently the much weathered and battered remnants of small communal houses scattered here and there at intervals of a few hundred yards. How many such mounds there may be I can not tell, for after riding among them for a mile and a half I turned northward up Chaves Canyon into the heart of the red mountains. The ruins are located close to the mouth of small mountain valleys where the floods from summer storms spread out, and where the soil is of the sandy type best adapted to cultivation in so dry a region. Agriculture would readily be possible, provided only there were an assurance of flood-water sufficient to support the crops every year instead of only in good years.

The next 4 miles of the road lead up the narrow valley of Chaves Canyon where there is no room for agriculture. Then the trail comes out upon an upland stretch 8 or 9 miles wide between the divide at the head of Chaves Canyon (7,150 feet above the sea) and the main continental divide (100 feet higher) at the head of Satan's Canyon. Most of the drainage here runs centripetally toward the shallow, temporary sheet of water known as Smith's Lake, at an altitude of about 6,900 feet. Much of the land is rocky, especially near the divides, and the rest is less sandy and thus less propitious than in the region at the base of the cliffs. Nevertheless there are several hollows into which flood water flows and where fields of corn are rudely fenced off by the Navajos. No one except a white trader, however, lives here permanently, which is not surprising, since the total area of the fields within sight of the road is probably not more than 30 acres. Yet here, as in so many other places, the people of long ago were fairly numerous. Without deviating from the road one passes ruins in four places, the total number of houses being about 10 and of rooms 70, which would provide accommodation for about 50 people. These houses were of a different sort from those that we have investigated in the south. They were communal dwellings made of rough stones and probably plastered with mud, but now reduced to low and almost invisible mounds. To-day the only permanent supply of water is in Smith's well, 12 feet deep. The lake often dries up for six months at a time, and any reservoirs that the former inhabitants could have built would scarcely have been more permanent. The ruins are too small to prove anything when taken by themselves. They are worth mentioning simply because they show how numerous are the traces of ancient habitations and because they bear so marked an appearance of great age.

North or northwest of the continental divide a large number of valleys break through the white and brown cliffs, which correspond to the red cliffs of the southern side, and debouche upon a vast rolling plateau like that upon which Thoreau is located. Here, just as on the other side, the mouth of each canyon forms a center around which clusters a group of ruins. For instance, at the mouth of Satan's Canyon, down which runs the road to the main center of Chaco Canyon at Pueblo Bonita, the most prominent feature of the monotonous landscape, as one looks out from the mouth of the valley, is the circular stone tower of Pueblo Viejo or Kin Yäʼa, 30 feet high and 15 in diameter. Four stories can still be counted in it, and not many years ago there are said to have been five, although the upper parts have now fallen. The tower rises from a stone fort or sanctuary, about 150 by 80 feet in size. The whole structure is built of blocks of brown sandstone which have been broken and smoothed with surprising accuracy, considering that the ancient inhabitants did not possess metal tools. All the stone must have been brought from the mountains on the backs of men or women, no slight task considering that some of the blocks are 4 feet long, 1 foot wide, and 6 or 8 inches thick, and must weigh 300 to 400 pounds. Aside from the circular tower the fort contains 21 rooms which are still distinct; these are much larger than the rooms of ordinary dwelling-houses, and vary from 10 by 12 to 20 by 30 feet. Probably the larger ones were never covered with roofs. We can not be sure of this, however, for the ancient people knew how to utilize wooden beams, as is evident in the tower, where the different stories appear to have been separated by floors built of wood. Apparently the inhabitants did not for the most part dwell in the fort itself, but in less pretentious and more extensive structures round about. These are now reduced to long rounded mounds of varying height. Evidently some parts had one story, some two, and some probably three. They were built of stones like the fort, but with less care and with smaller blocks less painstakingly squared. Within a radius of a quarter of a mile of the fort eleven communal dwelling-houses can be counted. Reckoning the average size of the rooms as 9 by 10 feet, which is the approximate size of those excavated in similar ruins, and allowing for some parts having two stories and a few three, the total number of rooms in this village was probably over 300, or enough for a population of 250 people.

Kin Yäʼa is not the only ruin in this immediate vicinity. About a third of a mile to the west another and larger one, nameless so far as I could ascertain, has an extent of at least 800 feet from north to south. It appears to have been composed of a number of large communal houses, built close together. Most of the houses were apparently one story high, and were constructed without much stone. At the south end of the village, however, there was a large house, 90 feet long, having at least two stories and possibly three. Half a mile north of Kin Yäʼa, still a third ruin has three or four houses and possibly 100 rooms.

Whether any more ruins exist at the mouth of this particular valley is not certain, but probably others could be found. The next valley to the west is a small one, yet at its mouth the usual series of ruins is found. I saw two, both of them being groups of small low mounds where a few families had gathered stones to build their little hamlets and utilize the waters during the period of floods. Still farther west lies the valley in which the Indian agency is located. Here small ruins having six or seven houses occur in three places. The Indian traders and the one white sheep-rancher in the neighborhood say that this valley and its neighbor on the east contain other ruins which I did not see.

Westward from the agency a number of other valleys debouche from the mountains, but I had no time to examine them. In one of these, Indian Creek, 8 miles from the agency, there lives an Indian trader, Dalton by name, who has been in the country many years. Within a mile of his store, either up or down the dry bed of Indian Creek, he states that there are 15 to 20 small ruins of from one to six or eight rooms. Apparently the former population was large compared with that of to-day. Some of the ancient people seem to have left their habitations much earlier than others, the small ruins in the minor valleys having been abandoned long before the large ones in the valleys of greater size, such as Satan's Canyon. In some cases drinking water can now be procured by going a long distance to springs; in other cases one can not see where it was obtained. This, however, may be neglected while we turn our attention to the way in which the people procured a livelihood.

The people in this part of New Mexico, like the Hohokam of the south, were preëminently agricultural, and must have obtained practically their whole living from the soil. That they lived in one place permanently is clear, not only from arguments like those used in connection with earlier ruins, but from the large size of their fort and from the great amount of work which they lavished on its construction. How numerous they were we can not say with certainty, but at the mouth of Satan's Canyon it scarcely seems as if there could have been less than 500 or 600 people. The next valley may have had 20; the next (in which the agency is located) 25, and so on. In a stretch of 16 miles from Satan's Canyon westward past the agency and Dalton's, there must be at least a dozen valleys, and the whole number of people probably mounted well up toward 800 or more. At present the Navajos cultivate as much land as they can, although they do it carelessly because the crops so often fail. In the 16 miles under discussion, there are now only two families, according to Mr. Dalton, who raise corn enough actually to support themselves through the entire year. The rest depend upon their flocks and buy corn from outside sources. The whole number of families who own cultivable land amounts to only 25, he says, and the total amount of land is only 65 acres, or sufficient to support 33 people according to our Arizona estimate. Mr. Dalton, however, thinks that the number would be less than this, for he says that the families who actually carry on cultivation do not raise more than one-tenth enough to support themselves, supposing that they had to depend on what they could raise and not on sheep. Judging from the poor appearance of the crops, and the frequency with which they fail, he is probably not far from right.

The plateau extending northward from the base of the cliffs where the ruins just described are located is a desolate region, with no inhabitants save occasional wandering Navajo and one or two traders and sheep-men. It is now absolutely devoid of cultivation; nevertheless, it has a few ruins, which form the fourth of our five groups. Some of these are small, insignificant mounds, almost invisible, and apparently very old. Human bones and complete skeletons facing the east, and with jars or shallow bowls on their breasts, are often found near them, and it was clearly the custom of the inhabitants to bury their dead close to the villages. This is quite different from the habits of the builders of the larger and apparently later villages, for their burials are rarely found and seem never to be near the villages. Seemingly, as Bandelier long ago pointed out, we have two types of civilization, an older and more widespread one dwelling in small hamlets far remote from present sources of water, and a later one clustering nearer the sources of water and building large, well-protected villages.

The second or later type of ruins has already been illustrated by the castle of Kin Yä'a or Pueblo Viejo. A much more remarkable illustration, however, is found in the notable ruins of Chaco Canyon. This is a steep-sided, flat-floored valley cut in the plateau 25 or 30 miles north of the cliffs at the northern base of the Continental divide. The ruins center around Pueblo Bonita, the home of a trader, and the only permanently inhabited place for many miles. Within half a mile or less of this place there are six large ruins and at least ten small "suburban" ones. Farther away there are others scattered up and down along the canyon and in the lower parts of the chief tributary valleys. Most of the ruins are on the valley floor, but a considerable number are high on the level plateau, far above the bottoms of the valleys. None of the larger ones, however, appears to be at a great distance from the main lines of drainage, or from places where a supply of drinking-water might be secured with a moderate amount of care in the construction of reservoirs. Often a considerable climb would be required to surmount the high cliffs and carry the water up from the stream, but that would not be of great importance among a primitive people.

The ruins in this region, more than in any other that we have yet discussed, present an appearance of solidity and permanence. (Plate 3, B.) This does not mean that they were necessarily occupied more permanently or even as much so as the others, but being built of stone they are massive and durable, and have withstood the ravages of time. Moreover, they appear to be younger than at least a part of those which we have been considering. The larger ruins are strongly built, compact structures with lofty stone walls, solid at the base, but sometimes pierced with windows at the level of the upper stories. Each one must have sheltered several hundred people, as appears not only from their size, but from the amount of labor required in building them. The largest are thought by some students to have had as many as 1,000 to 2,000 denizens. It must have taken a good many people and a long occupation to build a large number of villages all located close to one another, and all together presenting an appearance which seems quite massive even to the modern traveler accustomed to the great cities of the present and to the ruins of the most famous empires of the past. The permanence of the villages is still more evident when we consider the amount of labor involved. We must constantly bear in mind that the American aborigines not only had no iron tools, but were also not blessed with beasts of burden. Yet all the stone for the main ruins, such as Pueblo Bonita itself, appears to have been brought from a considerable distance, a mile and a half, so it is said, in this case. The trail can still be seen along which the rock was brought to the top of the cliffs to be thrown down to the place where it was needed. A few unused rocks still lie at the top of the cliffs. Of course it is possible that certain villages were built and immediately abandoned according to the frequent assumption of archeologists and ethnologists, but this seems improbable, for people would scarcely go to so much labor again and again if they expected soon to move away. Moreover, they could not have accomplished all that the ruins still show, unless they had lived in the place many years. This is important because it means that in this one limited valley or its environs a rather dense population, numbering probably several thousand people, had to be supported year after year, in good times and bad. So dense a population would drive out all the game in a short time and could not depend upon that source for food; nor could they have lived upon wild products, for there are none that would support more than about one man for every square mile. Therefore all these people must, it would seem, have been dependent upon agriculture, a conclusion by no means new, but which means much when considered in reference to climatic changes and their effects.

The problems of agriculture, of water-supply, and of the location of villages are all closely connected. We have just seen that while the small and apparently ancient type of ruins may be located far away from any visible supply of water, the larger, more compact, and apparently later ruins are always located fairly near to a permanent source of drinking water. Nevertheless, water was evidently not the only desideratum in choosing the sites of many villages. Pueblo Alto, near Pueblo Bonita, lies on the plateau high above the valley on the north side, while the ruin of Hermoso lies in a similar situation on the other side of the canyon. There are traces of an ancient spring about half a mile from Hermoso, but it is dry now and has been for an unknown period. As for Pueblo Alto, unless the inhabitants climbed down the cliffs they can have obtained water only from small reservoirs. In dry seasons, even with a considerably greater rainfall than now, both villages would probably have had to send their women down to the main canyon for water; clearly they were not located with any reference to ease in obtaining water. Nor were their situations easy of defense. Both Pueblo Alto and Hermoso are on the nearly smooth plateau in places of no special strategic strength. To be sure they are more or less completely surrounded by cliffs that can be scaled only with difficulty, but the cliffs are far away from the houses, and no attempt has been made to locate the villages in places surrounded and protected by natural barriers. The upland villages are removed from the main line of easy travel, but otherwise are not much more protected from sudden raids than are their neighbors in the valley. They have left their own record of the fact that, at least in their later days, they were harassed by enemies. The record takes the form of long walls which sometimes jut out half a mile from a village, apparently to furnish a shelter behind which to flee to the village in case of attack. Other evidences of the fear of enemies are found in circular shelters of stones, placed upon commanding hilltops or upon less noticeable elevations. Yet the villages themselves are not placed in sheltered spots but merely on some slight eminence in the midst of the generally level plateau. If, then, the plateau villages were not located with special reference to the most permanent water-supply, nor in the places most easily defensible, what was the determining factor in their location? The answer seems to be, "arable land." If the population was as great as we have inferred, the flat land of the valley bottom must have been inadequate to support so large a number of people, even if it could all be used. The choice apparently lay between putting the village in the main valley and climbing up the cliffs to reach the fields, on the one hand, or placing the village on the plateau and climbing down to the canyon for water, on the other hand. Some chose one way and some the other, but probably those who chose the valley fared best in the long run. If the climate became drier, the upland fields might have to be abandoned, but those in the valley bottom could still be cultivated. Moreover, a decreasing supply of water would not occasion them more work in order to get enough to drink, whereas the necessity of descending to the valley for water in dry seasons would become a distinct tax upon their lofty neighbors. Finally, the people up above, being already impoverished, would be especially subject to irreparable injury in the raids of enemies, and so not only would have to build works of defense, but would perhaps be killed off, forced to migrate, or impelled to take to plundering on their own account. So long as the rainfall sufficed to render cultivation possible upon the plateaus, the villages there had a reason for existence. If present conditions prevailed when they were built, their dry, exposed location is difficult to explain.

After all that has been said, it may seem almost superfluous to speak further of the inadequacy of the present agricultural resources of the Chaco region, yet it is necessary because scientific writers have so largely maintained that the present water-supply is adequate for as large a population as ever at any time dwelt here. Oddly enough, the majority of thoughtful, non-scientific observers who have lived or traveled extensively in New Mexico have largely been of the opposite opinion and have agreed with President E. McQ. Gray, of the University of New Mexico, who, when asked his idea as to the conditions prevailing in pre-Columbian times, remarked: "I never thought of entertaining any other view than that the change in the territory was due to a change in the water-supply."

In order to assist in a final settlement of this question, if such a thing be possible, let us consider the present conditions of agriculture in the once populous Chaco Canyon. There are now in the canyon two Indians who are reasonably sure of a good crop of corn each year. I saw their farms, unbelievably dreary wastes of drifting sand in the bottom of the canyon where two large tributaries join and where the level of ground water is consequently higher than anywhere else. In the vicinity of the chief ruins, 2 or 3 miles upstream, the level of ground water is 20 feet below the surface of the lowest part of the valley, but at the farms water can always be secured close to the surface, although farther downstream the level again declines. The abundance of sand, as well as the high level of ground water, is also helpful, since the sand, by acting as a mulch to prevent the evaporation of the ground water, is an extremely useful adjunct of agriculture. In spite of these advantages neither of the two Indian farmers has obtained a good crop every year in recent times, although, according to the local story, one of them failed only because he did not build the necessary dam to retain all the water in an extremely dry year; the other failed because of the absolute lack of water. Various other Indians cultivate parts of the valley floor, but with the most meager success. In good years the corn is said to grow to a height of 6 to 7 feet; in other years it is only 2 or 3 feet high, and often it fails completely.

In the last sixteen years, according to Mrs. Wetherell, the wife of a trader whose husband was killed by the Indians, there have been only two good crops. In three years, 1902, 1903, and 1904, the Navajos planted corn as usual, but, with the exception of the two fortunate men already mentioned, got no returns. In the remaining years the crop varied all the way from almost nothing to fair. The reason for its failure in the dry years does not appear to be that the method of cultivation is poorer than in the past, but simply that the summer rains, upon which corn and beans (the only possible crops among the aborigines) entirely depend, never fell at all or else did not fall until so late that the frost came before the crops could ripen.

Modern engineering and the process of digging deep wells and pumping by means of engines might enable a few families to live comfortably in the Chaco Canyon, but that has nothing to do with the matter. The former inhabitants, no matter how high may have been their civilization, were primitive people who had no good tools and no knowledge of mechanics. They built dams and ditches whose remains are found in all parts of the Southwest, but the abundance of these remains is the best sort of proof that the people knew nothing of any but the simple and obvious methods of flood irrigation. If they had practised any other sort, if they had built dams of cut stone or had constructed canals of cement, or if they had been able to raise water out of the depths of the ground, traces of their achievements could scarcely fail to be found. Dry farming, it need hardly be said, is to-day out of the question in this arid portion of the country. How far it was practised in the past is not yet certain, but if our reasoning as to the location of the villages on the plateaus (and especially as to the small, remote ruins) is correct, there probably was a good deal of it in very ancient times.

The crops of the past appear to have differed from those of the present not only in quantity but in quality. I can not vouch for the truth of this, but Mrs. Wetherell and others state that the corn cobs and squashes found in the ruins are uniformly large like those now raised only in good years, and not at all like the stunted little products of ordinary years. Whatever may have been the quality of the crops or the extent of dry farming, one thing seems evident: Chaco Canyon and the neighboring plateaus to-day, even with modern methods of irrigation, could support only a fraction of the number of people who appear to have lived there in the past. Either the climate was different or the ruins are utterly misleading in their indications as to the density of population.

Before leaving the Chaco Canyon a word should be added as to the succession of races in this region. The small villages or hamlets located upon the plateau at a distance from the main valleys seem to have belonged to a people different from those who later built the large villages, which, however, frequently contain evidences of an occupation previous to that whose remains are now chiefly in evidence. For instance, at Pueblo Bonita, Pepper (who excavated for the American Museum of Natural History in New York) found evidences of an older occupation 10 feet below the one which we have been discussing, and there is a possibility of an intermediate occupation. Three feet under the level of the main plain upon which stand the ruins of Pueblo del Arroyo traces of old walls can be seen extending 100 feet beyond the present ruins; the lowest part of these walls is 5 feet below the present surface. At the little ruin opposite Pueblo Bonita some of the walls extend downward 3 feet lower than the others, suggesting that old walls had fallen into ruins and were then built upon once more after 3 feet of material had accumulated. Elsewhere, at points farther up the canyon, old walls are said to lie 12 feet below the present surface. The material in which all these walls are imbedded seems to be the ordinary silts of the valley floor. Without further study no positive conclusions can be based upon them, but they are suggestive. Apparently the Chaco Valley was occupied at least twice. Possibly, although this is pure surmise, the first occupation was at the time when the remoter ruins of the small type were also inhabited. Then the place was abandoned, wholly or in part, and the river deposited from 3 to 12 feet of silt before the next occupation took place. Such deposition, as we have seen, would normally occur in a time of unusual aridity, and hence may be of significance in our climatic problem.

The final abandonment of the ruins may also throw light on physical conditions. We have already seen that at the end of the period of the main occupation of the ruins the inhabitants were in straits not only to get water enough, as is clear from their many dams and little reservoirs, but also because of enemies, as appears from the defensive walls and from the way in which in neighboring regions the villagers often took refuge in inaccessible spots upon high hilltops or in deep canyons. An examination of the rooms seems to indicate that the population dwindled gradually. Many rooms are found sealed up, or full of rubbish, showing that for a long time before their final abandonment they were not in use. All these things are exactly what would be expected if the climate had become drier. They can also, to be sure, be explained equally well upon various other suppositions, such as the incursion of enemies, or of new people with new ideas, the ravages of disease, the superstitious fear of rooms in which a death has occurred, and other similar theories. These might be given the preference were it not for the evidence which we shall present later when we come to discuss the measurements of trees. Meanwhile it is merely necessary to call attention to them.

One other matter also comes up in this connection: The region of which the Chaco Canyon may be considered typical appears once to have been densely populated, but is now one of the least habitable places in the United States. When the Spaniards arrived in America the ancient inhabitants appear already to have vanished, since no mention is made of them in Spanish chronicles. Moreover, their pottery and methods of architecture were different from those of any tribe of Indians which existed in later times. The fact that the people had vanished proves nothing, but it is interesting to note that it is exactly what we should expect if they were driven out by aridity. Here where the country is exceptionally dry they would disappear sooner than in better-watered regions, such as the Rio Grande Valley, where the Pueblo Indians had their chief center. We shall return to this general subject later and its bearing will be more fully apparent.

One of the best places for the study of the relation between older and younger ruins is the Pajaritan Plateau, 20 to 30 miles northwest of Santa Fe. I had the good fortune to be conducted to this region by Mr. Kenneth M. Chapman, the assistant director of

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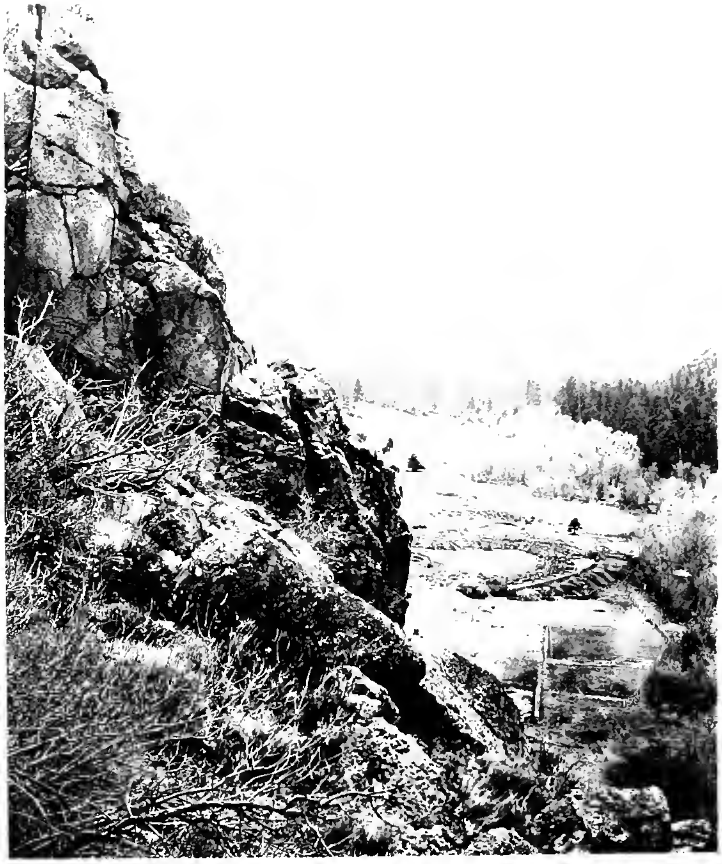


B

A. Ruins of Tyuonyi in the Canyon de los Frijoles
B. Ruins of Pueblo Bonita in Chaco Canyon.

the Archeological Museum of New Mexico, to whom reference has already been made. Leaving the stiff shade trees of the well-watered, grassy plaza of Santa Fe, we took the narrow-gage line of the Denver and Rio Grande Railroad to the lumber piles of the villageless station of Buckman on the Rio Grande itself. Crossing to the west side of the river, we left the barren desert vegetation of yuccas, sagebrush, and cacti which prevails at this altitude of 5,500 feet, and climbed 1,000 feet to the plateau. The road winds up over variegated layers of volcanic tuff of pale pink, yellow or brilliant orange shades, interspersed with the darker blue-black of basaltic lava flows and capped with brick-red columnar tuffs. These volcanic rocks form the Pajaritan Plateau, a gently sloping, deep-soiled district, sharply cut by numerous canyons formed by streams running eastward from the Jemez Mountains. The plateau is a beautiful region covered with forests of juniper and piñon, which at higher elevations give place to stately yellow pines set in open order with stretches of sparse grass between them. The scenery is uncommonly attractive as one drives slowly along, sometimes on the level, again dropping into the hollow at the head of a cañon, and then climbing the slope once more to the upland, where one looks out east or west at great snowy mountains. Yet in spite of the deep soil, the grass, and the trees, we saw no sign of modern habitation, for except in a few insignificant spots in the bottoms of the cañons where irrigation is possible, all the great plateau is too dry for cultivation below a level of about 8,000 feet.

Soon after we had reached the main top of the plateau we came upon the first of the great number of ruins which are scattered in all parts. These particular ones were cliff dwellings of the usual type, caves dug in the soft volcanic rock on the side of a shallow canyon, and fronted by rooms made of blocks of the same soft tufa. The number of such caves and cliff dwellings in this one Pajaritan Plateau is literally thousands. With them are associated other villages of the same type as those of the Chaco Canyon. After crossing several minor canyons we reached the edge of the deep Canyon of El Rito de Los Frijoles, or Bean Canyon, where a precipitious cliff falls away 400 feet or more at one's feet. Looking over the brink of the cliff one sees, far down at the base of a precipice, a structure which at first sight suggests a Greek amphitheater; it is the village of Tyuonyi, excavated by the School of American Archeology at Santa Fe in the four seasons from 1908 to 1911. The plan of the ruins is symmetrical, a circle slightly flattened on the north side, and containing five to eight tiers of rooms arranged like the seats of a theater. Across the flattened end where the stage would be expected, a line of rooms contains the remnants of three circular chambers or "kivas," designed for religious purposes, and apparently analogous to the larger circular or elliptical structures which are found so commonly among the ruins of adobe and wattle villages in the Santa Cruz Valley and other regions farther south. (See Plate 3, A).

The Canyon of El Rito de Los Frijoles contains not only the main ruins of Tyuonyi and several smaller ones, but also a great number of caves and cliff-dwellings. Doubtless the caves were at first the chief homes of the aborigines; but as time went on and a higher stage of civilization was reached, they were used chiefly as store rooms, and the main life of the households was conducted in rooms located in front of the caves and built of stone plastered with mud. Often a house consisted of three tiers of rooms in front of a cave; and in many cases the rooms were built one on top of another to a height of three stories. Most of the rooms, like those of all the primitive people of the Southwest as well as the modern Pueblos, were entered through the roof. The small size of the rooms, not over 6 feet by 10 on an average, is surprising. The reason commonly assigned, however, seems convincing. On the high Pajaritan Plateau the temperature often falls to 10° F. below zero. The relatively dense population must quickly have used up all the available dead firewood for many miles around, and it was no easy task for a primitive people, unsupplied with iron tools, cut to firewood sufficient for anything more than the necessities of cooking.

Farther south, or at lower altitudes, the rooms were larger, for there it was easy to keep warm.

The low temperature of the Pajaritan Plateau does not appear to have diminished the number of inhabitants. Frijoles Canyon alone, within a distance of not over 1.5 miles up and down the narrow gorge, had a population of fully 2,000 souls according to the estimate of Dr. Edgar L. Hewett, Director of the School of American Archeology, who was personally in charge of the excavations. The actual number of rooms, including the village amphitheater, the caves, and the cliff dwellings, appears to have amounted to about 3,000. At present, according to Judge Abbott, who owns all the valley except the ruins, the amount of land that can be irrigated amounts to 21 acres. The ancient Pajaritans could scarcely have existed unless they cultivated the plateau where now not a solitary person makes a living from the fruits of the earth. Therefore Dr. Hewett is unqualifiedly of the opinion that the climate of the past was moister than that of the present.

Let us now consider an apparently older and more widely scattered occupation of the country. During our visit to the plateau we watched carefully not only for cave dwellings and villages of the Tyuonyi type, but for the little mounds which here and there, at a distance from all the main sources of water both past and present, proclaim the location of houses scattered over the plateau. One not closely on the watch may miss these entirely, for they are merely small heaps of stones. In the space of 7 miles we saw houses of this type within sight of the road in 49 different places. Inasmuch as several houses were often clustered in one group, the total number of dwellings was 67. They were obviously mere farm-houses, but some had from 8 to 20 rooms, and must have been inhabited by more than one family. Therefore in our 7-mile ride through the open, park-like forest we must have found the dwellings of approximately 100 families within sight of the road. It would be a populous farming district in any part of England where one could find 100 families on 7 miles of road. We can not, of course, assume that every one of these houses was occupied at one time, but it is not probable that any large number were vacant at a time when new ones were being built. The blocks of stone used in their construction would seem to be too valuable to permit of their being wasted when new houses were to be erected. Even in these days of metal tools, beasts of burden, and wheeled carts many great ruins of western Asia are in imminent danger of being utterly destroyed by the natives, who carry away the stone for use in new houses, even though the present population is only a fraction of that of the past. In the days of the Pajaritans, when the blocks of stone had to be hewn with stone axes and carried from the quarries in the canyons on the backs of men or rather of women, we can scarcely believe that the people were so extraordinarily industrious, or so superstitious, that for generation after generation they would leave good stones in ruins close at hand and go to the labor of obtaining new ones. Therefore we are inclined to believe that at the height of the prosperity of this region practically every one of the present ruins was a house occupied by one or more families.

These scattered little ruins of farm-houses, almost unnoticed even by the archeologist, present one of the most interesting problems in American archeology. The potsherds found in them are different from those in the larger villages or in the majority of the cliff-dwellings immediately around them. The pottery of the farms, as Mr. Chapman points out, is almost wholly a fine-grained ware painted white and adorned with geometrical designs in black. In the larger, more modern ruins, however, only a little of this is found, while the commonest kinds are a coarser white ware with more abundant curves in the designs, and a wholly different type of red ware adorned with black figures decorated with a species of glaze. These differences, coupled with other evidence, such as the manifestly greater age of the small isolated ruins, show that here, even more plainly than in the Chaco region, we have to do with two occupations as distinct from one another (and from the later and far less extensive Pueblo occupation) as is the modern American occupation from that of the Spaniards. The first inhabitants spread far more widely than their successors. They seem to have felt no need of being near the main sources of water nor yet of gathering together, as the later people did, in places which could easily be defended. For a long period before the advent of the enemy which finally displaced them, their lives were apparently free and comfortable in their high forest homes. How or why they vanished is as unknown to us as is their origin, but perchance we shall learn the story little by little. It will not be a story of peace and monotony, for those are not the conditions which prevail when a race comes into a country nor when it is forced out. We can scarcely doubt that raids, plunder, repeated invasions, great distress, and the final disappearance of one type of civilization and its replacement by another were the order of events.

This painful process of a change of civilization took place not once alone, but at least twice. Formerly the cliff-dwellers who built the compact villages like Tyuonyi and Pueblo Alto were supposed to have been of the same race as the modern Pueblo Indians, but recent investigations indicate that this is not true. Possibly, indeed probably, the modern Pueblo is related to the second or village-building type of ancient inhabitants, whom we may call Pajaritans in distinction from the still older type who may perhaps be classed as Hohokam, but the relationship is not close. The bones of the dead, exhumed after centuries, tell something of the tale. The modern Pueblo Indians are brachycephalic according to Dr. Hrdlicka;* their heads are relatively broad, as anyone can tell by looking at them. Some, however, are dolichocephalic, with long heads, but these are in a minority. The present Indians are clearly of mixed descent. Their predecessors, on the contrary, were of a pure race, predominantly long-headed like ourselves. Therefore we infer that they were conquered by invading broad-heads, and that finally the invading broad-heads and as many of the long-heads as had neither fled nor perished became amalgamated into a single race. Perhaps the ancient farmers, the medieval villagers, and the modern Pueblo Indians were not the only races which have passed across the stage of history in the prehistoric days of America. In other parts of the Southwest faint glimmerings of still other cultures are seen, which show that change and movement have been as characteristic of the ancient history of America as of that of Europe and Asia.

We have seen that at least two types of prehistoric civilization spread widely over areas which are now uninhabitable. The early Hohokam farmers have left their ruins over all parts of the high plateaus and of the great lowland valleys far from any visible source of water, even for drinking. The later Pajaritans, both village- and cliff-dwellers, did not spread so widely, but they managed to live and raise food in hundreds of valleys where this now seems to be impossible. Let us next inquire whether the latest of the original American types of civilization, the Pueblo Indians, were ever blessed with climatic conditions such that they, too, could inhabit regions whence drought now excludes them.

The well-known ruins of Tabira, popularly called Gran Quivira, are located about 6,000 feet above the sea near the center of New Mexico, about 65 miles south-southeast of Albuquerque. They lie on a rounded hill, about 200 feet above a broad, open valley draining toward the south and a mile or more in width. The ruins consist of two distinct portions, Pueblo and Spanish. The ground area is about 700 by 350 feet, with a few buildings outside these limits. All the structures were built of light-gray limestone broken into roughly rectangular blocks. The exact source of the building material is not evident, although there is stone of the same sort visible in small outcrops not far away. The character of the stone, however, is such that it would be difficult to get it out in large quantities without the aid of explosives. Inasmuch as the village was evidently built long before the coming of the Spaniards, we must assume that the Indians put themselves to a vast amount of labor in the process of quarrying, squaring, and transporting the stones of their numerous houses.

* See Hewett, Edgar L.: The Pajaritan Culture. Papers of the School of American Archæology, No. 3, p. 341.

Many of the dwellings appear to have been of two stories, and the height of the heaps of rocks makes it probable that some had at least three stories. The rooms are all small as is usual in this region, the majority not exceeding 7 by 9 feet. The exact number of rooms has never been counted, but some approximate idea may be obtained. If we assume that only half of the 5.5 acres covered by the ruins was actually built upon and that the rooms including the walls had an average size of 10 feet by 10, there would have been about 1,100 rooms on the ground floor. The upper stories may be put at 400 rooms, although the actual number was probably greater. This gives 1,500 rooms as a moderate estimate, which would mean at least 1,000 people.

When the Spaniards came to the country, at the beginning of the seventeenth century, the village of Gran Quivira was evidently one of the most important in the district. Otherwise the canny fathers would not have built here one of their largest missions. Building stone was fairly easy to obtain, it would seem, inasmuch as the walls of the church are 5 feet thick. Possibly this was because a portion of the village was in ruins, and the stones from it were available as building materials for the large church and other structures which the Spaniards erected. Nevertheless, the number of natives must have been considerable, or there would have been no reason for a mission. The beginning of the Spanish régime here, as in the rest of New Mexico, appears to have been peaceful and prosperous. Its end, so far as Gran Quivira is concerned, seems to have come shortly before the Pueblo rebellion, which culminated in 1680. Since that time the site has been left as a center around which a multitude of traditions has gathered. One ascribes its destruction to an earthquake, another to a flow of lava bursting forth some miles away, and still a third speaks of a river which has now disappeared.

The truth seems to be that there is no village now at Gran Quivira because there is no water and the land is too dry for successful cultivation except in years of good rainfall. A ranch is located in the valley below the ruins, but it is not permanently inhabited, although a little cultivation is carried on. Settlers have recently come into the region 10 to 15 miles to the north, but are having a hard time. If the rainfall is propitious they can exist, but in 1909 none of them raised enough to live on. It scarcely need be added that all depend upon deep wells for water. The Pueblo Indians, so far as we can gather, were like their Hohokam predecessors in knowing nothing of lime or mortar and had no facilities for making water-tight cisterns. Often, however, they constructed reservoirs, which were their main dependence. One such reservoir still remains intact at Gran Quivira. It lies about 0.25 mile east of the village in the mouth of a shallow arroyo, as dry valleys are here called. The reservoir is only about 75 feet in width and 5 feet deep. The owners of the ranch down below in the main valley say that during 7 years of life here they have never seen any water in it except immediately after rain. My visit took place in the early spring of 1911, after a more than commonly rainy season. The day previous to that on which I started from the railroad at Willard, 30 miles to the north, there was a heavy storm, and during the drive we were soaked in a pouring rain. Nevertheless, the next morning the reservoir contained no water and showed no sign of having held more than a small pool the day before. In all the region within a score of miles of Gran Quivira there is only one permanent spring. That is located 7 miles to the west at Montezuma, and, as might be expected, has its own ruins of an ancient village. Strangely enough, however, the Montezuma village was evidently abandoned long before Gran Quivira. This suggests that the difficulty of raising crops was a more serious matter than the difficulty of obtaining water. At Montezuma the land does not lie so low and flat as at Gran Quivira and is not flooded, as are the lowlands of the latter place, during summers when the rainfall is large.

In addition to Gran Quivira another similar ruin of a Spanish mission deserves to be recalled in order to show that the phenomena just described are not isolated. This is the ruin of Buzani, which has already been mentioned as lying about 12 miles below Caborca on the lower Altar River in northwestern Mexico. Caborca, it will be remembered, is the last inhabited place on the river. Farther downstream there is no water except during the brief season of floods. At Buzani a few Papago Indians cultivate a considerable quantity of land in good years, but do not live there all the time. They might remain through the year, for they have a well, but it is very deep, and the labor of drawing water is great. Here, as in the other case, the Spaniards established a mission in a place which sensible people would now scarcely choose for the purpose. I have not been able to ascertain the date of the Buzani church, and am not certain whether it dates from the seventeenth or eighteenth century, but probably from the latter. Its evidence is by no means so clear or pronounced as that of the Gran Quivira. In both cases, however, the point to be borne in mind is this: we have before us two theories which stand on an absolutely equal footing so far as innate probability is concerned. The only question is which one best fits all the facts. One theory holds that the climate of the past three centuries has been uniform; while the other assumes that there has been a change, the seventeenth century or at least its first half presumably having been considerably moister than the nineteenth, while the eighteenth was probably intermediate between the other two. Viewing the two theories without prejudice, it seems fair to say that the theory of change fits the facts better than the theory of uniformity.

We have now finished our survey of the ruins of the United States. Let us sum up our conclusions, and see whither they have led us and what possibilities they suggest. The evidence that the climate of the past was different from that of the present seems to be too strong to be ignored. The simplest mathematical calculation shows that where it is possible to raise food for only 10 people 100 people never could have found sustenance. Nevertheless, many men whose opinion is entitled to the greatest respect doubt the conclusion to which this simple sum in division would seem to lead. They admit that 100 people could never have lived in the places which furnish food for only 10, but say that the solution of the problem is not to multiply the ancient food supply by 10, but to divide the apparent population by 10. Their argument does not seem to be conclusive, because it involves the assumption that the people of the past were radically different from those of the present; yet such arguments are extremely difficult to discuss, because no one can assert that certain races of people may not have had habits quite contrary to those of the rest of the world. The burden of proof, assuredly, is on those who assume such peculiarities in the ancient Americans, and it seems as if they had not proved their point, but this is purely a matter of opinion. If there were no other way of settling the question it would be necessary to take up this matter step by step and discuss the exact degree of mobility among modern races of various degrees of development, and then to go on to an attempt at estimating the exact amount of food that could be supplied in the best as compared with the worst years. Then we should have to calculate the number of people who could possibly have made a living and to compare that with the number whom the ruins seem to indicate. Next we should have to estimate the amount of work which would be required to build such ruins as those of Pueblo Bonita, for example, and should have to determine how many decades or centuries of constant labor the construction of all the numerous ruins in and around the Chaco Canyon would have required on the part of the handful of people who could there find sustenance. When that was finished, we might perhaps be in a position to say just how phenomenal must have been the ancient race which migrated so quickly from place to place, and worked so hard in order to leave ruins that look as if they had been the work of many people instead of a few. By the time we had finished we should have made so many assumptions that our conclusions would be inconclusive, and we should end where we began.

The only way to arrive at a firm conclusion is to test the matter by some means which does not involve any assumptions as to the nature of man, either now or in the past. Such means are found in the old strands and terraces described in earlier chapters. Even these, however, are not conclusive in certain respects. As to the alluvial terraces there is an alternative theory, that of earth movements, which has hitherto been so widely accepted that the student who has a bias against changes of climate is almost sure to incline toward it. As to the lakes, there can be little question that their high strands indicate moist conditions in relatively recent times, but when it comes to dating those times, we are once more at a loss to determine convincingly whether they belong to a period before or after the coming of the Hohokam. Taking it all in all, then, we may say that if we accept the reasoning of this volume as to the origin of alluvial terraces, and if we assume that the Hohokam were essentially like the rest of mankind, the evidence in favor of changes of climate is overwhelming. If, on the contrary, we accept the tectonic theory of the origin of terraces, and assume that the Hohokam were a highly peculiar people, we nullify the strongest arguments in favor of climatic changes, but we do not thereby prove that climatic uniformity has been the rule. We merely leave the matter open. The theory of uniformity needs exactly as much proof as that of change, for the inherent probability of the one is the same as that of the other. Yet, so far as I am aware, no one has ever adequately supported the theory of uniformity by means of an array of well-digested facts and figures, although many people have sought to disprove the arguments advanced as indicative of changes. The matter can not be finally settled until actual measurements of specific phenomena at specific dates can be obtained. Such measurements will be presented in later chapters. Meanwhile, the evidence already set forth is in itself so indicative of changes of climate, and agrees so closely with all that has been observed in Asia, that we seem forced at least to believe that a change of climate in the southwestern part of the United States is quite as probable as no change.

As to whether the supposed change from the past to the present was pulsatory or gradual the evidence is not so strong. The terraces, and to a less extent the lacustrine strands and gypsum dunes, seem to point to a pulsatory character. The human evidence is less conclusive. Since the pre-Columbian inhabitants of America began their work, however, the course of history appears to have been characterized by three chief epochs. In the first epoch man spread over wide areas, lived peacefully in small, unsheltered communities, and apparently was not particularly disturbed as to his supply of water. Then this population of early farmers disappeared. How or why or when, we can not tell. War, pestilence, drought, or any one of a dozen different disasters may have been the cause. Some of the people may have gone at one time, and others centuries later. All that we know is that they went and were succeeded by a people who lived a different sort of life. At first these later people may have been as peaceful and untroubled as their predecessors, but before they finally left their ruins they were forced to cluster around the main supplies of water, they were compelled to build dams and reservoirs in large numbers, and they were sadly harassed by relentless enemies. In their case, also, we have no exact knowledge as to whether war, pestilence, drought, or other causes finally overwhelmed them, but this much can fairly be said: All the disasters which have been suggested as the chief cause of their decline are the sort which would arise when the climate became dry, the crops failed, famine was rife, disease had free rein because of the weakening due to poor nourishment, and war and plunder were rampant because of discontent and suffering. How many of this second type of people were displaced at any one time, how long they suffered before they were driven out, and how long they had previously dwelt in safety no one yet knows. Probably they had disappeared, or their villages had been abandoned and they had become mixed with the invading Pueblos at least two or three centuries before the Spaniards arrived about 1600 A. D., for otherwise the early fathers would have heard traditions of them in greater numbers. More than that we can not say. Finally, the last type of aborigines, the Pueblo Indians, have had a history similar to that of their predecessors, but on a much less extensive scale. They, too, in the early part of the seventeenth century seem to have been able to spread out into regions not now habitable, and they, too, suffered stress and were forced to give up their old homes.

The history thus outlined is highly fragmentary. It is introduced here merely to call attention to the way in which studies like those of this volume may enable us to round out the outlines of early American history and assign dates to certain epochs. If the change of climate from the past to the present has been pulsatory, it needs no demonstration to show that in a dry country like the Southwest an epoch of abundant and, still more, of increasing rainfall would be marked by prosperity and by an increase in the density of population. Wars would be relatively scarce, or if they occurred they would be wars of conquest and expansion rather than pitiless raids like those of the hungry Arabs and the hordes of Genghis Khan. Such at least is the theory to which a study of the climatic vicissitudes of Asia seems to lead. When a change for the worse arose, and the country began to become drier, all sorts of distress would ultimately ensue. That drought brings famine, and that famine brings disease and pestilence, need no demonstration. That famine and hardship lead to robbery, raids, plunder, and kindred ills is also self-evident. That these things disrupt society and lead to war, misery, and the overthrow of civilizations is also clear. Doubtless other forces often conceal and often reverse the results which climate alone would produce, but even in the most advanced of modern countries few influences are more powerful than those of poor crops, poverty, and hunger. For example, Brückner* has shown that the volume of emigration from northwestern Europe to the United States has varied in close harmony with variations in rainfall and hence in the crops. Moist periods in Europe are in general coincident with moist periods in America, but in northwestern Europe an excess of moisture is injurious to most farm products, while in America it is favorable. Hence poverty at home has served as an expulsive force, while prosperity in America has been an attractive force, and the two together have caused a pronounced agreement between rainfall and emigration, as is illustrated in figure 7. To

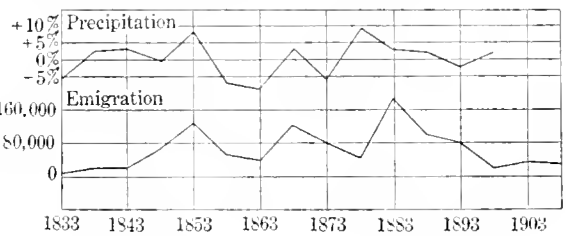


FIG. 7.—Rainfall and Emigration in Europe, after Brückner.

take another example, it is generally agreed that the United States had a Populist party largely because of a series of bad crops, and that the party died on the return of prosperity. If small variations of rainfall can produce such great results, a far more serious and prolonged succession of worse and worse years might well disrupt so primitive a civilization as that of the pre-Columbian Americans. If this is so, and if we shall ultimately find that climatic pulsations have actually taken place, we shall be able to say that in such and such centuries the conditions of climate were such that prosperity was the rule, and that agriculture was possible to such and such limits. In certain succeeding centuries, when conditions became worse, the inhabitants must have been forced to find a living within an area much smaller than heretofore, old habits must have been interfered with, war and strife must have prevailed, numbers of people must have been forced to move from

* Ed. Brückner: Klimaschwan kungen und Völker wanderungen in XIX Jahrhundert Internationaler Wochenschrift. Marz 5, 1910.

one place to another, and in general the conditions of life must have been revolutionized. In this way it is quite possible that we may be able to date and characterize some of the chief epochs in early American history.

As has already been stated, the more severe climatic variations of the present time appear to be in general synchronous in the United States and Europe. This was evident in the summer of 1911, when England was so dry as to be changed from a green land to a brown, and the eastern United States had the hottest, driest season for a century. If larger climatic variations are likewise synchronous in both hemispheres the chronology of climatic changes which has been worked out in Asia may assist in the elucidation of the unwritten history of America. In Asia each of several great dry epochs seems to have been marked by great movements of the nations and by the more or less complete reorganization of society in the regions which were most influenced. The first such epoch can be dimly discerned about 1200 B. C. At that time the ancestors of the Greeks came into their peninsula, the Hebrews entered Palestine, the Aramæans from Arabia spread out into Babylonia and all the neighboring lands, and Egypt was overwhelmed by invaders from both the Libyan and Arabian deserts. The next great period of aridity apparently culminated in the seventh century after Christ or thereabouts. Its approach seems to have been marked by the barbarian invasions of Europe and its culmination by the Mohammedan outpouring from Arabia. Finally, the third of the more important dry epochs came about 1200 A. D., when the hordes of Genghis Khan ravaged Asia from China to the Mediterranean. Besides these more intense periods of aridity there seem to have been others of minor importance, but these may here be omitted. Between the epochs of aridity periods of prosperity, expansion, and growth have apparently coincided with favorable conditions of climate. In studying the ruins of America we have thus far found no data which enable us to correlate the climatic history of the Old World and the New. Nevertheless, we find in each continent three main periods of prosperity and apparently of abundant precipitation in the drier portions. Perhaps this may be due to an actual agreement in climatic events. The ancient and widely extended farming population of the remote little ruins of our southwestern plateaus may have lived in the period of moist climatic conditions of which we seem to find evidence at the time of Christ and earlier. Their disappearance may have been due to the aridity of the period which culminated in the seventh or eighth centuries. Then the village people, the Pajaritans, may have flourished in the middle ages, a period moister than the present, but not so moist as the preceding propitious epoch. They may have been ousted by the twofold disaster of prolonged drought and fierce invasion which would have come to America about 1200 or 1300 A. D. if conditions here were like those of Asia. And finally, the occupation of places like Gran Quivira by the modern Pueblo Indians may be the result of propitious conditions following the dry period of the thirteenth century. Such a correlation between climate and history is as yet merely a suggestive hypothesis, but it may well be kept in mind in future investigations.

SUPPLEMENTARY STATEMENT.

Since the preceding chapter was prepared for the press there has come to hand a publication bearing the title "The Physiography of the Rio Grande Valley, New Mexico, in relation to Pueblo Culture," by Edgar Lee Hewett, Junius Henderson, and Wilfred William Robbins, Washington, 1913. The last thirty pages of this are devoted to an article on "Climate and Evidence of Climatic Changes," by Junius Henderson and Wilfred W. Robbins. In this article the authors in general adopt the methods set forth in "Explorations in Turkestan" and in "The Pulse of Asia." Their work was apparently completed prior to the appearance in 1911 of the first of my own articles on changes of climate in the United States. Therefore, their conclusions are of the more value because they were reached independently and without knowledge of the investigations described in this volume. They quote various authors for and against changes of climate, among whom Lowe, L. F. Ward, Hewett, Cummings, Hoffman, Morrison, Newbury, and Blake believe in changes, although several of them base their belief on very slight evidence. On the other hand, Holmes speaks doubtfully, and Cope, Fewkes, Mindeleff, and Bandelier are strongly opposed to the idea. None of these authors, however, goes into the question exhaustively. A quotation from Hewett* in regard to the Pajarito or Jemez Plateau will illustrate the extent to which the subject has hitherto been investigated:

"It appears that the abandonment of the cliff and pueblo villages of the plateau occurred from 600 to 800 years ago as a result of climatic modifications by reason of which the hardships of living at these sites became unendurable. The transition from plateau to valley life was not necessarily sudden. There is no evidence of any great simultaneous movement from all parts of the plateau. The change was probably accomplished within a generation or two, one village after another removing to the valley or to more distant places, as the desiccation of the plateau proceeded. There is at present not a single stream on the east side of the Jemez Plateau between the Chama and the Jemez that carries its water to the Rio Grande throughout the year. The ancient Tewa people were, as are their modern successors, agriculturists; hence, their living was dependent on the water-supply. Only the most primitive style of irrigation was practised and there is every evidence that the region was never rich in game or natural food products of any kind."

Henderson and Robbins take up the matter much more fully than their predecessors. Inasmuch as their work centered in the Pajarito Plateau, it will be worth while to quote what they say as to the Cañon de los Frijoles.†

"The ancient ruins in the canyon itself once must have housed some hundreds of people even if all the ruins were not inhabited contemporaneously, and there is nothing to indicate that they were not practically all occupied at the same time. Bandelier, who is conservative, places the population at 1,500. In addition, the ruins of old dwellings are to be found everywhere on the adjacent mesas and scattered throughout the other canyons which cut the plateau. The mesa dwellings are not so situated as to indicate that they were placed on elevated ground for protection from enemies, and it seems wholly improbable that their occupants would have lived in such places if they were dependent for food on crops in the canyons. It is also inconceivable that they would have lived on the mesas with their water-supply in the bottoms of the canyons, 450 to 600 feet below them, unless the canyons were already occupied and their tillable land was taken up by others. No extensive irrigation works on the mesas have yet been discovered which would provide irrigation for crops, and carrying water for irrigation to the mesas from the nearest present sources would have been quite impracticable, yet there is no reason to believe that corn could now grow on the mesas in the vicinity of these ruins. The country is not and probably has not been rich in game. It is difficult to believe that so many people would have built on the mesas unless they could have raised crops there without irrigation. With fertile valleys, good water, and better opportunities in the bottoms of the canyons for protection and seclusion from enemies, it seems very much more likely that they would have occupied the valleys alone unless there were more inhabitants than the limited valley areas would support. Hence a logical conclusion is that probably most of the dwellings in the canyons and on the mesas were occupied simultaneously at some period. The fact that it was not necessary to live near the fields would hardly account for the placing of the homes on the high, dry mesas, because locating them here would add to the distance and altitude to which the grain and water must be carried. It is also wholly improbable that any great number of springs was destroyed by earthquakes or concealed by the inhabitants on abandoning the dwellings, without many of them, or, indeed, most of them, revealing themselves now by seepage, while if destroyed by desiccation, that would put an end to them and stop seepage.

"If there has been progressive desiccation of the region it would be fully adequate to account for the abandonment of these ruins by the rather large population which probably once occupied them. Then, inasmuch as the same condition is found over a very large area, indicating that in the whole now arid region the aggregate population must have been very great, the question would arise, where did they go? It is not sufficient to say merely that they were driven out.

* Hewett, Edgar L.: Antiquities of the Jemez Plateau, New Mexico, Bull. 32, Bur. Amer. Ethn., p. 13, 1906.
† Hewett, Henderson, and Robbins: Physiography of the Rio Grande Valley, pp. 53, 55, and 56.

A general migration to some distant region where conditions are more favorable would probably have left a well-defined trail in the traditions of the whole region. Numerous traditions of local migrations are known, but all should be scanned with care before acceptance. It seems to the authors that a much more reasonable explanation of the known phenomena is this: If the rainfall slowly decreased, conditions must have become very gradually more severe. More and more frequent droughts and accompanying starvation periods would result, during which the weaker members of the tribe would perish, not altogether from starvation, but from the reduction of their powers of resistance to disease, cold, and other hardships through want of sufficient nourishment. Thus the general physique of the tribe would be preserved by the weeding out of the unfit instead of weakening the physique of the tribe as a whole. As the severity of such droughts increased it is probable that minor wars for the possession of the small, better-watered tracts would occur, still further reducing the various tribes and decreasing the aggregate population of the region. Occasional minor epidemics would be apt to reduce still further their numbers, especially if they occurred during periods of drought. Thus it is reasonable to suppose that as a natural result of desiccation the population decreased so gradually that the decline could be discovered only by very accurate statistical records or by a general comparison of the numbers living in the region at widely separated periods. In this way the depopulation would progress slowly by natural processes and therefore would not attract the attention of the inhabitants and would leave little impression in their legends or traditions. The remnant of the population would gradually move in small bands to situations favorable to agricultural pursuits, thus becoming widely dispersed. The foregoing changes would be expected to occur in a region which was slowly drying up, and present conditions are just such as one would be led to expect. Hence it seems very probable from the archeologic evidence that there has been progressive desiccation."

It is interesting to find that in the publication under discussion botanical evidence receives considerable attention, one of the joint authors, Professor Robbins, being a botanist. On page 56 he discusses a matter of considerable importance. My own notes contain many references to phenomena identical with those he describes, although I have not discussed them so far as New Mexico is concerned for the same reason which makes Professor Robbins hesitate, that is, because the number of exact observations is limited; yet the fact that his observations and my own agree so closely adds to their value.*

"While it is true that during 3,000 years some species may be altered to a slight extent, others may be introduced by various means, and others may come into existence suddenly (mutation), and that the relations of formations and associations of plants may have changed in some measure, yet it is highly improbable that there has been a marked and widespread modification of the flora within that time. However, the relation of the two principal plant formations of the region seems to afford some evidence of progressive climatic change. This may be seen in the stress zone between the pinon pine-cedar formation and the rock-pine formation. Pinon pines and cedars grow in drier situations than do rock pines. In the area under discussion rock pine occurs on the higher parts of the mesas, back toward the mountains, while pinon pine and cedar are confined to the lower portions, down toward the rim of the Rio Grande Canyon. At a distance of 1 to 3 miles back from the Rio Grande the two formations meet and here there is a battle for occupancy of space. If in this struggle between these two plant formations the pinon pine-cedar formation is the successful competitor and gradually encroaches on the rock-pine formation, and if such encroachment is widespread, this condition probably indicates progressive desiccation of the country. That is the condition in this region. If the rock-pine formation were extending into the territory of the formation below it, there would be rock-pine seedlings as outposts of the invasion, and their presence would be evidence that conditions in the new territory were favorable for their growth. From the lower extension of the formation rock-pine seedlings are almost entirely absent. The outermost individuals are large trees, in many cases the largest of the formation, possibly several centuries old, indicating that in the early stages of their growth conditions were more favorable for the species to obtain a start and that no such favorable period has occurred since. Pinon-pine and cedar seedlings do occur at the stress zone, although not in greater abundance than at any other point in the formation. The whole aspect of the line of stress between these two formations shows that the pinon pine-cedar formation is encroaching on the rock-pine formation, a condition which would not exist unless there is progressive desiccation which is tending to make the debatable territory unfavorable for the rock pines and better suited for pinon pines and cedars."

* Robbins: Physiography of the Rio Grande Valley, p. 56.

The final conclusions of Professors Henderson and Robbins are summed up in twelve statements, part of which refer to geological matters whose relation to man has not been definitely determined. The others are as follows (pp. 68–9):

"1. The climate of the Rito de los Frijoles and surrounding region does not now permit the raising of corn without irrigation except in perhaps a few favored localities.

"3. It would not require a very great increase in precipitation to make the raising of hardy, drought-resisting varieties of corn possible without irrigation in localities where it is not now possible.

"4. Distribution and extent of ruins throughout the Southwest, including the Jemez Plateau, strongly suggest different conditions a few centuries ago, with a more general distribution of springs and streams and sufficient precipitation for the cultivation of areas not now fit for agriculture and for the irrigation of tracts where it is now impracticable, thus indicating a probable change of climate within at most the last ten to twenty centuries. There is some direct historical evidence pointing the same way.

"7. There is some botanical evidence, although meager, of a change in climate within four or five centuries and of the still-continuing desiccation.

"8. On the whole, in the opinion of the writers, various lines of evidence point to progressive desiccation of the region since the beginning of the pueblo and cliff-dwelling period, with no important evidence inconsistent with this view, although the change in population may possibly be ascribed to other causes.

"9. This progressive desiccation, if it has occurred, doubtless has been accompanied by numerous slight fluctuations in climatic conditions, just such as are matters of record during historic time, wet and dry and warm and cool cycles alternating.

"12. Evidence of recent desiccation is not conclusive, but the problem is probably capable of solution by further cooperative investigation along lines suggested in this discussion. Several lines of evidence point to slight progressive desiccation in the Southwest within the period of human occupancy. Such desiccation would satisfactorily account for present conditions, and no other explanation yet suggested seems adequate."

On the whole, the conclusions of Professors Henderson and Robbins as well as of Dr. Hewett agree with those to which we have been led in the volume. This agreement is important, inasmuch as their publication is the first in which independent workers other than the present author have taken up the methods discussed in this volume and have applied them to a region in America.

CHAPTER X.

SOUTHERN MEXICO AS A TEST CASE.

The testing of a theory can be accomplished in at least three ways. First, it can be applied to new regions; second, it can be confronted by new lines of evidence; and, finally, it can be investigated by new observers employing different methods or at any rate coming to the problem from a different point of view. In the present investigation we have already used the Southwest as a new region to be compared with the old regions of Asia and the lands of the Mediterranean. Let us now take still a third great region and once more make a test. Southern Mexico lies at a distance of from 1,200 to 1,500 miles from Arizona and New Mexico. This is a small matter compared with the 8,000 or 10,000 miles which separate those regions from the parts of Asia where our chief conclusions as to that continent were reached. Nevertheless, the difference between Arizona and southern Mexico is greater than between Arizona and Turkestan. This is because, although Arizona has summer rain like that of Mexico, its most important precipitation is the winter type characteristic of the zone where westerly winds and subtropical aridity are the dominant features of winter and summer respectively. In going from Arizona to southern Mexico, on the contrary, we cross the trade-wind zone and enter the edge of the zone of equatorial rains and calms. Hence we are able to subject our theories to a more severe test than would be possible even if we completely encircled the globe, but remained in the same zone of climate. The change is so great that we are able not only to test our theory in a distinctly new region, but also to confront it with certain new lines of evidence.

The investigations in Mexico to be described below were made during the spring of 1912. Those here discussed were confined chiefly to the City of Mexico, in latitude 19.5°, and to Oaxaca and Mitla, in latitude 16°. In both of these places evidences of changes of climate appeared to an unexpected degree. In discussing this matter, let us take up, first, the recent fluctuations of the lakes near the City of Mexico; second, the evidences of a change in the conditions of the Basin of Mexico during the time of ancient civilizations; and third, the alluvial terraces found near Mexico and in Oaxaca. A fourth type of evidence, namely, the peculiar location of the ruins of Yucatan, together with those of Guatemala and Honduras, is so new and important that it will be left for later chapters after we have considered the trees of California.

In the *Monthly Weather Review*, for November 1908, I have discussed the City of Mexico and Lake Tezcuco in their relation to changes of climate. In considering this matter here, I shall largely follow that article, but shall add new facts which have come to light since it was written. The City of Mexico lies 7,400 feet above the sea near the salt lake of Tezcuco and the tributary fresh lakes of Xochimilco and others. The basin containing these lakes is similar in its general features to that of the Great Salt Lake in Utah, Lop Nor in Central Asia, and Seistan in Eastern Persia. Accurate historic records of the country extend back to the time of the Spanish invasion in 1519, and before that we have fairly reliable traditions for at least 200 years more. Taking merely the 600 years for which we now have data, we find that during that time there appears to have been a slight but appreciable change of climate in Mexico similar to that which has apparently occurred in Asia. The evidence is somewhat masked because the natural course of events has been interrupted by various works of man, such as the dikes, canals, and tunnels which have been built since 1446 to regulate the waters of Tezcuco and its three tributary lakes. Nevertheless, there have been certain periods when nature has triumphed over human endeavor and the waters have returned to the level which they would naturally occupy if man had never interfered. A comparison of the chief epochs of this sort seems to afford some ground for the belief that the climate of Mexico has passed through fluctuations like those of Asia, on the one hand, and of more northern regions in America, such as California and New Mexico, on the other hand.

The great authority on early Mexico is Humboldt, whose "Essai Politique sur la Royaume de la Nouvelle-Espagne" was published in 1811 as the third part of the "Voyage de Humboldt et Bonpland." Later and less authoritative writers, such as Prescott and Romero, follow him closely, adding little that is new. Humboldt specifically states his belief that the climate of Mexico in his day was more arid than it was at the time of the founding of the capital about 1325 A. D. He attributes the change in part to undefined meteorological causes whereby evaporation has exceeded precipitation, and in part to the reckless destruction of forests by the Spaniards. He is sure that the level of Lake Tezcuco has fallen, through natural causes as well as through the works of man, and cites this fact as the chief evidence of a change of climate.

According to tradition, the Aztec founders of Mexico, like most of the world's great races, came from the north. After a century of adventurous wanderings, enlivened by the vicissitudes of war, conquest, and slavery, they appear to have reached the shores of Lake Tezcuco about 1325 A. D. Hoping for peace and safety, they located themselves on some small islets several miles from the shore. There they laid the foundations of the present proud City of Mexico by sinking piles into the marshy shallows and erecting upon them light huts of reeds and rushes above the reach of the water. During the succeeding century, according to Humboldt, the city grew and prospered and its rule spread over the neighboring regions. It was still an island city with houses on piles, with canals instead of streets in many cases, and with canoes in place of beasts of burden. Sometimes it suffered when the lake rose more than usual. The first well-authenticated event of this kind is recorded by Torquemada,* a monk who lived in Mexico from the middle of the sixteenth century well into the seventeenth. It happened in the early years of the reign of Montezuma, who became king in 1436 A. D. In this year the water "submerged the whole city and the inhabitants travelled in canoes and barques, without knowing how to remedy matters nor how to defend themselves from so great an inundation." The next year was also phenomenal, and Torquemada enlarges on the abundant crops and great prosperity, which, he says, are affirmed by all historians. At about this time the first known dike was built in the year 1446 A. D. If it were not for Torquemada's direct statement as to the great rain and abundant crops we might suppose that the dike happened to be built then merely because of an advance in the art of engineering; or because the increasing number of buildings in the city caused the land to settle, as it has done in recent years, when the erection of the new National Theater, for instance, has caused a local subsidence of 4 or 5 feet which is evident to the most casual observer by reason of the warping of the pavements of the streets. It seems probable, however, that the building of the dike was due more to climate than to any other cause, for the water did not remain at a high level thereafter, but near the end of the fifteenth century, fell so low that the city suffered much distress because canoes laden with supplies of food could not come in as formerly from the surrounding country. When Cortez came to Mexico in 1519 the water had again risen and the capital was still a western Venice. He describes it as located on an island two leagues from the mainland. In order to besiege it effectively he was obliged to build brigantines, and in these he was able to sail completely around the city, except for a small distance on the southwest

* Fray Juan de Torquemada: Los Veinte i vn Libros Rituales y Monarchia Indiana, etc., etc. Edition of 1723. (The original edition is 1615.) Book II, Chap. XXXVII, p. 157. For these references to variations in Mexican lakes, I am indebted to the researches of Mr. Adolph Bandelier.

side toward Chapultepec, where the water was too shallow. The small boats engaged in ordinary traffic sailed everywhere, however, not only on Tezcuco, but on the other lakes and on the connecting rivers. It is not evident whether this was a permanent condition, but in 1553, as appears below, we have evidence of a special inundation.

Two or three generations after the Spanish conquest the condition of the City of Mexico had changed. It had ceased to be an island, the canals had become dry, and wheeled vehicles had taken the place of canoes. This result was due in part to the construction of additional dikes, but nature apparently had been the main agent in the matter. Such seems to have been the opinion of Torquemada. He is quoted by Prescott (page 33):

"As God permitted the waters which had once covered the whole earth to subside, after mankind had been nearly exterminated for their iniquities, so He allowed the waters of the Mexican lake to subside in token of good will and reconciliation after the idolatrous races of the land had been destroyed by the Spaniards."

The waters rose again, however, for, to quote Torquemada,* "in this same year 1604, it rained so much in the month of August that the lake of Mexico was filled with all its plains, so that the waters covered nearly all the city and reached such a point in some streets that people passed in canoes, and I myself passed San Juan in this manner. The inhabitants lived carelessly, and forgetful of the previous danger of the same kind in the year 1553 when Don Luis de Velasco, the First, was governor. . . ." This wet period continued, for we are told that in 1607 the town of Tultitlan was inundated for the third time with great loss of houses and fields. To prevent such occurrences in the future a tunnel was built to carry off the surplus water of the Cuautitlan River. It might be supposed that, after the construction of the tunnel, the lake would never return to its natural condition. In 1629, however, during a season of uncommonly heavy floods, the tunnel was stopped up completely. The City of Mexico was flooded for a time and was in great straits during a period of rainy years lasting till 1634. Thereafter it became dry once more, although neither the tunnel nor the old dikes were in a condition to prevent the rise of the water. Again, from 1675 to about 1755, the tunnel was closed, being filled with earth for an unknown distance. At the same time also the dikes were in poor repair, breaking whenever the water rose higher than usual; yet the city continued to stand on dry land, though sometimes a year of exceptional rains caused the water to rise sufficiently to flow into some of the streets, but not enough to do any serious damage. Taken as a whole the history of the lake appears to have been characterized by fluctuations of considerable magnitude. How far these fluctuations agree with those in regions farther north will appear in a later chapter after we have considered the data derived from trees.

The evidence just presented is in itself too slight to justify any conclusion derived from it alone. Only by bringing together many diverse lines of evidence can we ascertain the truth even approximately. Fortunately, Mr. Manuel Gamio, under the direction of Professor Franz Boas, has recently been engaged in archeological excavations on behalf of the International School of American Archeology and Ethnology, and has done some work which is significant for our present purpose. The hamlet of San Miguel Amantala, near the village of Azcapotzalco, lies on the edge of the lacustrine plain of the City of Mexico, not far from the base of the hills on the west. This portion of the plain is dotted with little mounds which mark the sites of villages or small groups of houses built by the Aztecs and full of the typical pottery, images, and other relics of that people. Elsewhere the plain is strewn with the scattered fragments of another and older type of civilization, which is known as that of San Juan Teotihuacan, from the great pyramids of that name on the eastern border of the basin of Mexico. The San Juan relics never occur in mounds of the Aztec type except for a few stray bits which have been carried in by accident. This indicates that the two are of distinctly different dates, as indeed we know from other

* Loc. cit. Book v, Chap. LX, p. 728 B; and Chap. LXX, p. 756.

evidence. Some of the mounds of Aztec age appear to be merely accumulations of earth from the adobe roofs and walls of the ancient dwellings, but others appear to have been built of set purpose. This suggests that for some reason the earlier people built their houses directly upon the plain, while the later Aztecs raised theirs upon mounds. To Professor Boas this fact seems to indicate merely that before coming to the Mexican plateau the Aztecs had probably acquired the habit of building elevated structures and that this persisted throughout their history. Possibly, however, the elevation was an advantage for purposes of defense; or perhaps, at the coming of the Aztecs, the level of the lakes was so high that in times of unusual rain the villages were occasionally in danger of inundation, although during the days of their predecessors, the San Juan people, the plain may have been so dry that no such danger existed.

In one of the sites marked by San Juan pottery Professor Boas has made an excavation in which he finds the following section from the top downward:

(A) 1 or 2 feet of fine, dark surface soil full of bits of San Juan pottery.

(B) 6 inches to 2 feet of "tepetate," or "caliche" as it is called farther north, in layers from 1 inch to 1 foot in thickness. It is mixed with bits of San Juan pottery, and is interstratified with layers of well-rounded gravel containing pebbles up to 2 or 3 inches in diameter. The "tepetate" is a white calcareous deposit which is frequently formed in dry regions where a large amount of water evaporates. It is usually considered characteristic of rather arid conditions. Here at Azcapotzalco it is frequently faulted a few inches, as if the ground had sunken a little.

(C) 4 or 5 feet of "culture layers" full of San Juan pottery intermingled with ashes, fire-places, and the foundations of ancient houses.

(D) 5 or 6 feet of fine sand, often in pockets or in slightly cross-bedded bands. This is intermixed with finer sandy materials and a certain amount of clay like that which forms the bulk of the overlying culture layers. Fragments of pottery of the same San Juan type, together with bones and angular stones as much as a foot in diameter, indicate that men lived here when the layers were being laid down, although there are no foundations.

(E) 11 or 12 feet of gravel and sand growing coarser downward, and at the base containing cobble-stones several inches in diameter. The pebbles are mostly well rounded, as if they had been carried far in running water, although a few angular pieces are found, especially in the more clayey portions of the sand. San Juan pottery occupies the upper 5 or 6 feet, but only in small quantities. The fragments are often angular, showing that they have not been carried far in running water. The lower 5 or 6 feet contain quite a different kind of pottery, belonging apparently to the type which Professor Boas has called the Mountain culture. It is much more archaic than the San Juan or Aztec types, and it is certainly older, since it lies lower. Whether it persisted until the time of the later cultures we can not tell. Professor Boas says that as yet it has nowhere been found on the surface of the plain, although it is common in small areas scattered among the surrounding mountains. Hence its name. The pieces found by Professor Boas in his excavations were all well rounded, showing that they had been carried some distance by running water or, in other words, that they had been brought in from the mountains.

At a short distance from the main excavation Professor Boas found that the gravels of this formation die out. Minor excavations in several places led him to conclude that the main gravel just described indicates the location of a river bed less than 100 meters wide and extending in a north-and-south direction. Outside the river bed, but at the same level, the coarseness of the decomposed tufaceous matter increases a little, and the material is more sandy than above or below, indicating sorting by moving water. In the sandy material the archaic pottery of the Mountain culture is found in large amounts. It is not stream-worn or rounded, and the paints with which it is decorated are still fresh. Clearly it has not been carried far, which indicates that the plain near the old river, or torrent, must have been inhabited. Whether this pottery is of the same age as the worn fragments in the river bed is uncertain. It may be younger, for Professor Boas thinks that there may have been a gradual transition from the Mountain culture to that of Teotihuacan.

(F) At the base of the gravels a dark, compact clay is found to a depth of about 7 feet. It contains almost no sand, but is full of plant remains, and of hydrated iron which stains it yellow. The formation looks like the deposit of a swamp or of the edge of a lake. It is sharply separated from the overlying gravel in a way to suggest a drying up of the swamp and a sudden bringing in of materials by streams which had formerly had their mouths nearer the mountains. So far as the clays have yet been studied they contain no pottery or other evidences of human occupation.

(G) Finally, the lowest formation thus far penetrated is a light-colored sand which Professor Boas thinks to be lacustrine.

The single section here given is of course inconclusive. The transition from one type of deposits to another may have arisen from a change in the course of streams by reason of an earthquake or volcanic eruption, or it may have been due to a tilting of that particular portion of the earth's crust. The full history of the basin of Mexico can be ascertained only by means of a large number of excavations well scattered over the whole area. Nevertheless, the present section is important. Our purpose in Mexico, it will be remembered, is not to build up a new theory, but to test one which is founded upon a great number of facts in widely scattered parts of both Asia and America. We want to discover whether new facts found in other regions disagree with the theory and compel us to modify it, or agree and allow us to carry it into still other fields. Hence it is important to see that in this particular case, the only one of its kind where a rigorous test is yet possible in this particular region, the facts agree closely with what would be expected if the climate of Mexico has varied in harmony with what seems to have been the case in other parts of the world. The apparently lacustrine deposits of (G), and the swampy deposits of (F), to begin with the oldest formation, suggest conditions of decided moisture with such an expansion of the lakes that the floor of the basin was uninhabitable and the people were forced to live in the surrounding hills where they developed their mountain culture. The succeeding gravels suggest a change to drier conditions whereby the shore of the swamp or lake retreated and streams began to encroach upon the old water-covered bed. At the same time the death of vegetation upon the mountain slopes, because of the aridity, would permit the floods to wash down large amounts of coarse gravel, with which would be mingled rounded, waterworn bits of pottery from the mountain villages, as appears in the lower part of formation (E). During this dry time, if such it really were, the people of the mountain type apparently expanded from their restricted habitat among the arid hills, and spread out over the relatively moist plain as is indicated by the unworn pottery at the base of (E) in the portions of that formation outside the river channel. A little later, the San Juan culture, perhaps that of an invader, made its appearance, the village in question being close to the base of the mountains, or on the very edge of the plain, as is indicated by the fact that its pottery is present in the gravels, but is free from marks of wear by running water. By the time that deposit (D) began to be laid down the San Juan people were living not far from the site of the excavations. When (C) was being formed conditions were very much as now. (B), on the contrary, with its layers of "tepetate" and gravel, suggests a return toward aridity, while (A) brings us back to the present conditions. If the elevation of the Aztec mounds, built since the deposition of (A), really has anything to do with the danger of flooding it may indicate a slightly moister time such as that of which the traditions give a suggestion in the fourteenth century, while now in the nineteenth and twentieth centuries we are back once more in dry times. The whole importance of the line of reasoning here followed is quite independent of the fact that the specific phenomena here described are subject to other possible explanations. It lies rather in the fact that the explanation here offered harmonizes with a vast number of other facts, both in Mexico and elsewhere, while the other explanations take little account of anything outside of the narrow range of the phenomena immediately to be described.

Turning now from archeology and lake-beds to alluvial terraces, we find that the kind discussed in previous chapters have not been described at any length by the geologists of Mexico. Nevertheless, they are said to be abundant in the states of Chihuahua, Durango, and elsewhere in the northwest, and my own observation proves them to exist in large numbers and in a highly developed condition in Sonora, and also in the vicinity of Monterey in the northeast of Mexico, along the railway line from Laredo to Mexico City. Through the courtesy of Dr. Jose G. Aguilera, Director of the Geological Institute of Mexico, one of his assistants, Mr. Ygnacio S. Bonillas, was permitted to spend some days with me in studying the region around the City of Mexico. Thanks to Mr. Bonillas's thorough knowledge of the local geology, I was able in a short time to see things which it would have taken weeks to find alone. Northwest of the city the volcanic hills are deeply seamed with rugged ravines descending from high mountains. There in four small valleys we found terraces of the kind under discussion. The presence of revolutionists within 3 or 4 miles of the places where we were at work, and in all the country round about, prevented us from examining others or from following any of the four up into the mountains, where the maximum development is to be expected. Nevertheless, the places pointed out by Mr. Bonillas were sufficient to indicate that, as a general rule, valleys of sufficient size and coming from mountains of sufficient height contain alluvial terraces of the type which elsewhere seems to be climatic. In various places the cross-section of the valleys is like that shown in figure 8. The calcareous caliche or "tepetate" on the top of the main

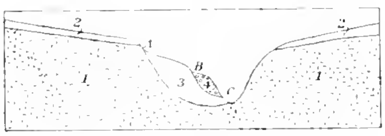


FIG. 8.—Cross-section of Alluvial Terraces in Mountain Valleys near the City of Mexico.

1 = Volcanic tuff. 3 = First alluvium.
2 = Caliche. 4 = Second alluvium.
A, B, C = Successive gorges.

volcanic deposits suggests a long dry epoch; the rapid cutting to form the gorge A indicates a pronounced uplift or else a period of comparative moisture, during which the streams were either of large volume or else were not overloaded with detritus because of the covering of the slopes with vegetation. In either case they were able to erode rapidly. The alluvial filling, 3, indicates either a tilting of the earth's crust back towards its original position or a period of aridity which would cause deposition either by diminishing the streams, or, more likely, by increasing their load through the death of vegetation and consequent releasing of the soil. The process of cutting and filling was repeated at least twice, and may have been repeated several times, although the evidence is now concealed or has been worn away.

Similar phenomena on a much larger scale occur farther south, especially in the valley of the Papaloapam River, nearly 200 miles southwest of Mexico City, between Puebla and Oaxaca. Here the terraces reach a height of at least 200 to 300 feet, and are developed to the number of four over long distances. Still farther south, in Guatemala, only 15° from the equator, terraces are found in an equally well-developed condition, as will be described later. They are of the same type as those in regions hundreds and thousands of miles away, and appear to be due to a common cause which can scarcely be anything but climatic pulsations. The constant occurrence of such terraces from Utah on the north through Mexico to the far south, and their high development even at the southern limit to which they have yet been traced, seem to be strong indications that climatic changes have taken place in Mexico as well as in the United States. The lakes of Mexico and the traces of ancient cultures in the strata forming the floor of the Mexican basin suggest that here, as elsewhere, the later changes have taken place since man reached a stage of comparative civilization.

CHAPTER XI.

A METHOD OF ESTIMATING RAINFALL BY THE GROWTH OF TREES.

By A. E. Douglass, Sc.D., *of the University of Arizona.*

In the great northern plateau of Arizona, lying at an average altitude of 6,000 feet above the sea, the higher elevations are covered with forests of yellow pine (*Pinus ponderosa*), a fine timber tree with a heavy cylindrical trunk and rather bushy top. The trees are scattered gracefully over the plains and hills and, with the remarkable absence of undergrowth, render travel through their shady midst attractive and delightful. For centuries these magnificent pines have stood there, enduring the vicissitudes of heat and cold, flood and drought. They have not been subjected to a mild climate for, contrary to common opinion, northern Arizona has really a cold climate. Several feet of snow lie on the ground during the winter, and the summer days, though hot in the sun, are cold in the shade. Hence the growth of the trees is sharply limited to the warmer season. The climate of Arizona presents not only a strong contrast between summer and winter, but between successive years, the rainfall in some years being no more than a quarter as much as in others. This being the case, it would seem that the trees must contain some record of the climatic variations through which they have lived. Other methods of studying this matter enable us to go back only from twenty to sixty years to the beginning of meteorological records in Arizona. The trees, however, if they prove to convey any information at all, will yield data covering two to five centuries.

The possibility that the trees might serve as indices of the climate of the past led the author to begin investigation of the matter in 1901. His line of reasoning was as follows:

(1) The rings of a tree measure its food supply.

(2) Food supply depends largely upon the amount of moisture, especially where the quantity of moisture is limited and the life struggle of the tree is against drought rather than against competing vegetation.

(3) In such countries, therefore, the rings are likely to form a measure of the precipitation.

In planning the work three fundamental steps were anticipated. First, to prepare a curve of tree growth; second, to find if there exists in this any connection with precipitation; third, by carrying this back through long periods to find whether meteorological variations, if discovered, show association with astronomical phenomena.

Note.—Throughout the present investigation our purpose has been to employ as many different methods as possible and to apply them in as many places as possible. Our danger has been that the framer of a theory, having developed new lines of reasoning, is apt to become so convinced of their validity that he sees everything from a biased standpoint. Fortunately, however, we are able to neutralize this danger by means of a new method of investigation, a method entirely independent of those hitherto discussed, and one so exact in character that the personal opinion of the investigator has little influence upon the main results. This method was suggested by Professor A. E. Douglass, of the University of Arizona, in an article published in the Monthly Weather Review for June 1909, under the title "Weather Cycles in the Growth of Big Trees." It does not, to be sure, shed light on the problem of the influence of climatic changes upon human actions and history, but it enables us, by means of actual measurements, to ascertain exactly what kinds of changes have taken place and at exactly what dates. The final determination of these things is, of course, a long process, and can not be completed for many years, but important results can be obtained at once. In order that the reader may have a first-hand statement of the matter, I have asked Professor Douglass to contribute to this volume a chapter which shall embody not only his original work as described in 1909, but certain measurements which he has since made, and upon which he bases fuller conclusions. Professor Douglass's contribution is inserted without further comment.—E. H.

ADVANTAGES OF LOCATION.

The pine tree of northern Arizona lends itself peculiarly well to the investigation here contemplated. Not only is its situation favorable because of the absence of other vegetation and of all pests which might seriously alter the growth of the tree, but because the soil is of such a nature that variations in precipitation are quickly felt in the trees. Of still more importance is the fact that the relatively open and unobstructed character of the country makes the meteorological elements relatively homogeneous over a considerable area, and tree records from widely separated localities show similar features. The importance of this is illustrated by the conditions near Flagstaff. To the south of the town, where the tree records were obtained, the altitude averages about 7,000 feet, and varies only a few hundred feet from place to place. North of the town, however, the San Francisco Peaks rise about 12,700 feet, and the yellow pine extends up their slopes to about 9,000 feet. On the side of the mountain, exposed to the prevalent westerly storms, the snowfall is heavy. There are found all the springs and ranches, and the overland stage line to the Grand Canyon goes that way in spite of heavy grades, for there water can be obtained for the horses. On the east side there is little snow, barren park lands abound, and the traveler has a run of 25 miles between watering-places. This represents the disadvantage of the very mountainous region, for different sides of a high range present different meteorological conditions.

Southeast of Flagstaff the plateau country extends nearly 100 miles to the so-called rim, where the land drops off to the lower levels of southern Arizona, while to the southwest the rim is 50 miles distant. On the slopes of the rim the trees go down to an elevation of about 5,500 feet. Here the trees are peculiarly sensitive to changes in rainfall, since they live under severe conditions due to the decrease of the rainfall with decreasing altitude. They are so sensitive, indeed, that in extremely dry years the older trees sometimes omit the formation of any ring whatever. Such an omission is of course significant, but it is an exaggeration of the actual conditions and it leads to grave errors. Besides the trees from near Flagstaff, others were collected from the mountain around Prescott, southwest of the rim across the deep Verde Valley. Among the high and broken ridges of that region the rainfall on opposite sides of a ridge may vary greatly. Hence nearly 60 trees from various localities were measured before a growth was found close enough to Prescott to be compared minutely with records of precipitation at that place.

SEASONAL CONDITIONS AND TREE GROWTH.

The climate of this part of Arizona possesses the general characteristics described in an earlier chapter of this book. Because of the altitude, the winter temperature often falls from 15° to 20° F. below zero. Shallow valleys are especially subject to low temperatures, for in the absence of general or storm winds, such as prevail over the eastern part of the country, the cold air settles in the lowest places. Even in summer the temperature is often low and snowstorms not infrequently occur in May, and during the last 18 years one occurred in June. These conditions favor very perfect ring production, but the division of the rainfall into a winter and summer season is a disadvantage in the attempt to investigate climate by means of the growth of trees, for the spring drought naturally checks growth and some of the trees often act as if winter were approaching, and form a layer of hard wood like that characteristic of the fall. Usually such trees begin to grow again when the summer rains come, and thus form a double ring, but some stop growing entirely.

Meteorological records in northern Arizona are necessarily meager, yet not so deficient as might be expected. The country was first settled in the fifties, when gold was discovered in Arizona as well as in California, and lines of travel were established from Santa Fe westward across the plateau. The "blazings" on the pine trees marking the earlier roads are still to be distinguished. Soon after the opening of the country the government located military camps at various places, and from that time records of rainfall and temperature were kept. The record at Whipple Barracks, near Prescott, which was begun in 1867, has been continued to the present time. It is the longest consecutive record in the pine forest, and is therefore made use of below. Aside from rainfall, other meteorological elements, especially temperature, must have an effect upon tree-growth, but I have not attempted to include them in this work, for it seemed desirable to ascertain the degree of relationship of the growth of trees to one single element before going on to others. Moreover, it is probable that the various climatic elements have so distinct a relation to each other that the investigation of one will throw light on the rest.

The plateau and the climate are not the only features of northern Arizona which favor an investigation of the sort here contemplated. The yellow pine itself is favorable, because of its conspicuous annual rings. The differences between the soft, rapidly growing white tissues of the spring and summer and the hard, reddish layers formed in the fall are much less conspicuous in most of the common trees than in the pine. The sharp, outer edge where the growth of the hard, red layer is checked by the cold of winter gives a precise point from which to measure. The chief growth of the tree consists of a wide, white, pulpy, summer ring, whose cells are round and well-shaped. As conditions of growth become less favorable, the cells become lean and emaciated and take on a red color. The autumn ring thus formed is thin, hard, and pitchy. On the inner side it merges gradually into the summer ring, but on the other side it is sharply limited by the spring growth of the next year. Where a double ring is formed, the white portion of the secondary ring is usually narrow and poorly developed.

THE COLLECTION AND MEASUREMENT OF SECTIONS.

At the beginning of the investigation it was foreseen that enough trees would have to be measured to give a real average. The trees would have to spread over enough country and be sufficiently numerous to eliminate accidents of grouping and other minutely local conditions, and yet they must not extend into other meteorological regions; they must be numerous enough to be susceptible of division into groups, which show common characteristics and thus testify to the genuineness of whatever variations appeared. Work was begun in January 1904, when I visited the log yards of The Arizona Lumber and Timber Company, Flagstaff, and spent several hours in the snow, measuring the rings of section No. 1. For subsequent measurements Mr. T. A. Riordan, president of the company, most kindly came to my assistance by having thin sections cut from the ends of logs or stumps and sent to me in town, there to be measured more conveniently. Sections VII to XXV were cut at my direction on the spot where the trees grew, and where I was able to mark the points of the compass on the sections and otherwise identify and describe their location. These 19 sections were freighted to Tucson, where the work on them was done. The method of measurement consists in determining the radial thickness of each annual ring in millimeters. The average age of the trees was 348 years. The total number of individual measurements reached over 10,000.

In the first comparisons between tree growth and rainfall the measures from six sections only were used and comparison was made with the Prescott weather records, for the Flagstaff station had been in existence only 6 years. At that time there was no thought of any such remarkable relation between yearly growth and yearly rainfall as has since been found; therefore, such relationship was not even tested until later. For purposes of comparison, smoothed curves were used, "the nine-year smoothed" being the one chiefly employed. Inasmuch as we were then attempting to study the general condition of the country rather than the individual year, and as the influence of good or bad conditions of rainfall lasts some years, the average of the eight preceding years and of the year in question was plotted in place of the rainfall of any single year. From such smoothed curves a connection between the precipitation at Prescott and the annual tree-growth nearly 70 miles distant seemed evident. Later studies have confirmed this conclusion and show that the agreement between tree-growth and rainfall is fairly close when the two are measured at approximately the same place. For more distant localities an agreement in individual years is not to be expected, but averages of three or more years show strong similarity, even in places so far apart as Prescott and the Californian Coast, 500 miles to the west. As soon as it became evident that the method under consideration gave genuine results further measurements were made. Lists of the sizes of individual rings of each of 25 trees were prepared. The trees were divided into three groups consisting of: A, 6 trees from 3 miles south of Flagstaff; B, 9 trees from about 11 miles southwest of Flagstaff; C, 10 trees a mile west of the last group. A comparison of the three groups clearly reveals the general character of the longer periodicities hereafter to be discussed and shows many lesser variations common to the three groups. Interesting differences also appear corresponding to the location in which the trees grew. Group A dropped to strong minima in 1780 and 1880 more promptly than the others. This appears to be due to the fact that it grew in a porous limestone soil lying upon rocks full of crevices. The other groups grew on recent lavas, very compact and unbroken and covered with rather a thin layer of clayey soil. In the region where group A grew, the rain passed quickly through the soil and was not so well conserved as in the other groups where the water could find no convenient outlet.

Other interesting facts came to light. It was especially noticeable that a given year of marked peculiarities could be identified in different trees with surprising ease. For instance, this is illustrated in Plate 4, where shavings from three of the Flagstaff trees have been photographed, and the photographs have been enlarged to such a scale that the distance from the ring for 1898, indicated by the upper line of black crosses, to 1851, the lower line of crosses, is equal in all cases. The other lines of crosses indicate the noticeably broad rings of 1868 and 1878. An examination of the photographs shows that the most characteristic feature is a group of narrow rings about the years 1879 to 1884. These can be identified in practically every tree, and an examination of stumps, which were not measured, showed that it was easy to pick them out wherever one chose. Striking verification of this was found in the case of a stump near town which had been cut about 20 years previously. By finding this group of rings the writer was able to name the year when the tree was felled and the date was verified by the owner of the land. In the more recent work this same group shows conspicuously among Prescott trees, and in general 95 per cent of these trees have rings so characteristically marked that the identification of the same series of rings can be made with little doubt, whether at Flagstaff or at Prescott.

As a rule, the thickness of a given ring is not uniform on all sides of the tree. It varies for accidental reasons, and also according to the points of the compass. In the 19 trees of groups B and C the maximum growth occurs a little to the east of north. The average variation between the maximum growth in the northerly direction and minimum growth to the south is 12 per cent. The explanation of the increased growth to the north is in the increased amount of moisture on that side, due to the slower melting of snow and the decreased evaporation in the shade. For nearly all these trees, also, the ground had a gentle slope toward the south, so that moisture working downhill would come to the north side first. All of these facts agree in pointing to moisture as the factor of greatest influence in tree growth.

THE DATING OF RINGS.

In comparing the growth of trees and the rainfall over long periods of years, it is essential that the date of formation of any individual ring shall be certain. There is little danger that two rings will coalesce, for the cold winters at an elevation of 7,000 feet cause the seasonal growth to be sharply defined. The mean temperature of 29° F. in January is so different from that of 65° F. in July that the ring of one year is nearly always clearly

1898

1878

1868

1851

separated from that of the next. Nevertheless, the rings may be so thin that they can not easily be distinguished, and seem to merge into one, but a microscopic examination usually shows indications of a soft, white ring as well as of a hard, red ring for each year. As a rule, therefore, each annual ring is extremely well marked, and there is no doubt as to its purely annual or seasonal character. In some few cases, however, rings die out completely, while in others they are double. In the first investigation of the trees at Flagstaff, it was estimated that the results were subject to an error of 2 per cent, most of which occurred near the center of the tree. The more rigorous methods subsequently employed, however, proved that the error of unchecked counting in these trees was 4 per cent and lay almost entirely in the recent years. It was due chiefly to the omission of rings or the merging of several together, apparently from lack of nutrition. The number of trees in which serious errors are found is not sufficient to prevent the curves of growth and of rainfall from showing close agreement. Mistakes can be guarded against only by a process of cross-identification which will be described shortly. The effect of the undetected omission or the doubling of rings in individual trees is to lessen the intensity of the variations in the curve of growth obtained by the averaging of many trees. The errors may be divided into two classes: first, local errors of identity in small groups of rings in a few individual trees, which simply flatten the curve without affecting the final count; second, cases in which a given ring, in spite of attempts at cross-identification, is still in doubt, showing perhaps in half of the trees, and not in the other half. Such cases affect the final count but do not flatten the curve. One case of this sort will be noted below. It leaves a question of one year in the dating of all the earlier portions of the curve.

THE TREES OF PRESCOTT.

The problem of cross-identification is well illustrated in the trees of Prescott. These were measured in 1911 for the purpose of testing the conclusions derived from the Flagstaff trees some years earlier. Prescott was chosen because, as has already been said, the weather records there go back to 1867 with only slight breaks. From that date until 1898 the observations were made at Fort Whipple, about a mile northeast of the town, and from 1898 to the present time they have been taken on the southwest edge of town. The small breaks referred to were chiefly in the summer of 1869. These have been supplied approximately by comparison with the records in other parts of Arizona during the years 1866 to 1870, but there is still a question of several inches for the total July and August rains for 1869. The cuttings from tree stumps in the Prescott region were procured through the assistance of Mr. C. H. Hinderer, supervisor of the Prescott National Forest. The region about Prescott has been in the Forest Reserve since 1898, and no cutting has been allowed except by special permit, but by the records he was able to tell just when the trees had been cut. The trees used were all of average size, being several hundred years of age; the cuttings were made from the edges of the stumps and were intended to include the last fifty years or so. Sixty-four were measured and the data in regard to them are shown in table 1.

TABLE 1.—*Trees of Arizona.*

Group.	No. of trees.	Elevation.	Distance from Prescott.	Exposure.	Drainage.	Date of cutting.
1	8	6,125	10 miles SE.	Easterly........	Lynx Creek.....	1911, May and June.
2	24	6,420	8 miles S.	Westerly........	Groom Creek....	1909, July to Sept.
3	12	6,800	10 miles S.	Northerly.......	Hassayampa	1910, Oct. to Nov.
4	10	6,420	8 miles S.	Westerly........	Groom Creek....	1909, July to Sept.
5	10	5,400	1 mile S.	Northeasterly....	Granite Wash ...	1909, Summer.

Besides the cuttings shown in table 1, three others were measured, two in the first group and one in the third, but were finally omitted because their oldest rings did not date back to 1867, when the rainfall record begins. Two others in the first group, with 40 and 41 rings, respectively, one in the second with 38 rings, and one in the third with 41, were made use of, although they did not quite go back the necessary 43 years. The values of the deficient rings were supplied by extrapolation and comparison.

Of these five groups the first four were collected in the autumn of 1911, measured, and their average curves drawn. While the comparison with the annual rainfall gave very promising results, it was apparent that the agreement between growth and precipitation increases as the location of the actual rainfall station is approached This sustained the opinion of Mr. R. H. Forbes, Director of the Agricultural Experiment Station at the University of Arizona, that rainfall in the mountainous region about Prescott is extremely variable, and for individual years one point can not be judged safely from others. This made it necessary to get some samples from nearer town. Mr. Hinderer, therefore, went to the further trouble of finding some stumps which were near town, about a dozen in all, from which the ten sections of the last group were cut. These ten show so much greater agreement with the rainfall than do the others that they have been used alone in the final conclusions.

The chief feature of the Prescott series which places its results on a firmer basis than any previous work is the cross-identification of rings between trees. The extent and accuracy of this identification came as a surprise to the writer. After measuring the first 18 sections it became apparent that much the same succession of rings occurs in each, and thereupon the other sections were examined and the appearance of some 60 or 70 rings memorized. All the sections were then reviewed, and pin-pricks placed in the wood against certain rings. Certain characteristics were noted as common to all, for example, the red ring of 1896 is nearly always double, while the rings of 1884 and 1885 are wider than their neighbors. The most conspicuous feature was a series of compressed rings from 1878 to 1883, preceded by a very faint 1877 and then a long series of very wide rings.

Out of 67 sections averaging 50 rings each, only 6 gave any trouble at the start. In two of these, 2 rings were lacking, but when allowance was made for this defect, the identification of the remainder was satisfactory. Another section had 2 extra rings, and another had 2 extra and 3 lacking. The other two sections proved especially puzzling. It finally appeared fairly certain that one of them had the rings from 1879 to 1887 merged into one, and the rings from 1890 to 1895 merged into one. The other had the rings for 1890 to 1895 in one and 1898 to 1900 in one. Of these six troublesome sections, the first five were very slow growers. Hence it would seem advisable not to use extremely slow-growing trees any more than is necessary. In objection it may be urged that the trees do not grow continuously at the slow or fast rate, and we can not tell how much of the change is due to rainfall. On the whole, however, it seems advisable to exclude trees, or parts of trees, whose identification is extremely difficult. The inner rings, if well identified, may be extremely useful in carrying back early records, as the slow-growing trees are likely to be among the oldest.

The cross-identification of trees from the Prescott region was limited to an area only 10 miles long. It came as a surprise, then, to find that shavings from the Flagstaff sections, such as are shown in Plate 4, could be identified at once in terms of the rings at Prescott. The narrow ring of 1851 was at once seen to correspond to one in the Prescott series. The dense series from 1879 to 1883 likewise had its counterpart at Prescott and formed the portion of the sections which gave the most difficulties in identification. On the whole, so far as can be judged without minute study, the Prescott trees from relatively high elevations approximating the elevation at Flagstaff have a considerably closer resemblance to the Flagstaff section than do those from trees growing at lower altitudes. The process of cross-identification appears to be applicable to areas far removed from one another. Two trees out of three which were tested from the Santa Rita Mountains in southeastern Arizona, 200 miles from Prescott, were found to have rings which could readily be identified in terms of the Prescott series.

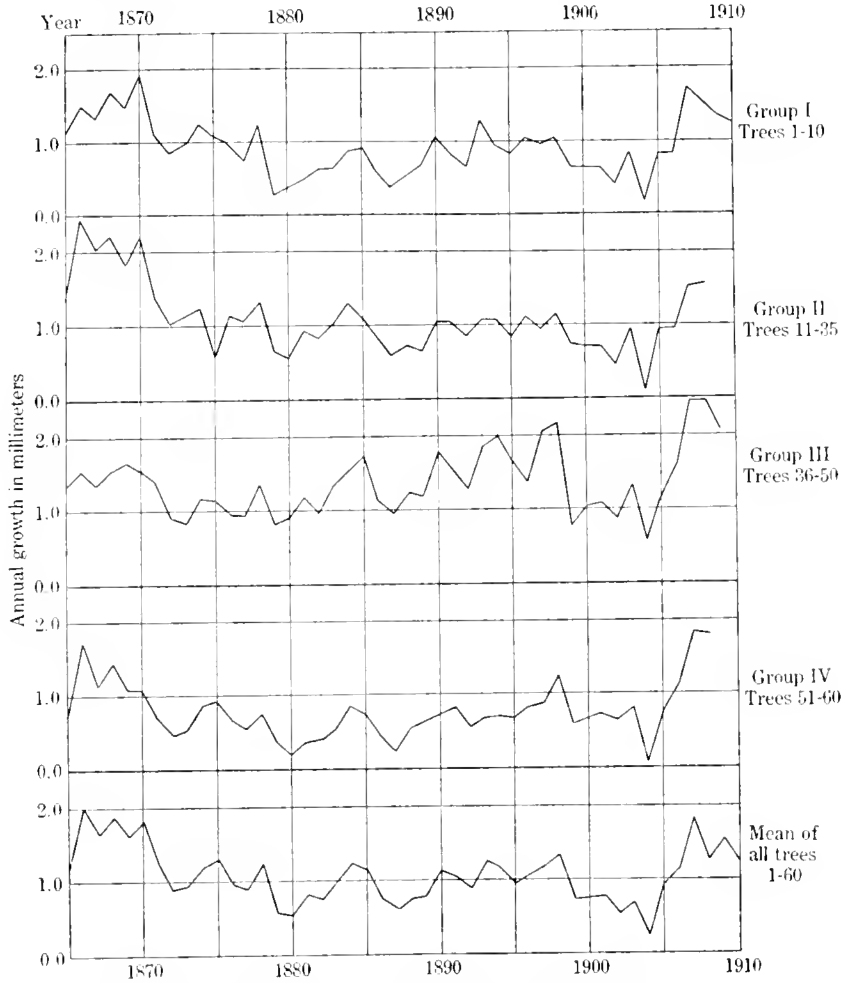


FIG. 9.—Annual Growth of Trees at Prescott, Arizona.

YEARLY IDENTIFICATION.

Let us now return to the application of the process of cross-identification to the trees at Prescott. Preliminary to the enumeration of the rings, a particularly clean section was selected and its rings were numbered consecutively; then all the other sections were compared with this as a standard. On the completion of 67 sections a careful review was made, and only three cases were found still to be questionable. At that time the following notes were made, the numbers being those obtained by counting back from the outer ring, that is, the ring of 1910:

> "No. 6 frequently double, mostly single, probably really 1 year.
> Nos. 31 and 32, mostly 1, occasionally clearly 2 years, still in doubt.
> Nos. 53 and 54 occasionally clearly separate, sometimes very close, often completely merged in one, still in doubt."

Upon further examination the following occurrences were noted: No. 6 was found double or triple in 46 cases and single in 21, but still uncertain. Nos. 31 and 32 were found to form a single ring in 22 sections, a double ring in 19, and to be clearly separate in only 11 cases. They seemed to represent one year. Nos. 53 and 54 were found to form a single ring in 6 cases, a double one in one, and clearly 2 in the remaining 24 cases for which sections were available; accordingly they were considered to represent two years. On comparing the plotted curve of tree growth with the curve of rainfall, the two were found to agree more closely if ring No. 6 were assumed to represent two years (1903 and 1904) rather than one, but the real evidence strangely enough came from Flagstaff. The cross-identification between the sections from Prescott and Flagstaff made it possible to identify, unquestionably, most of the rings, both before and after 1903, and Flagstaff plainly showed two rings in place of the doubtful ring or rings called No. 6 at Prescott. Hence this was apportioned to the two years 1903 and 1904. Apparently, if a sufficient number of comparisons be made, and if the trees thus compared be distributed over widely different localities, the yearly identification of rings may be made with almost perfect certainty.

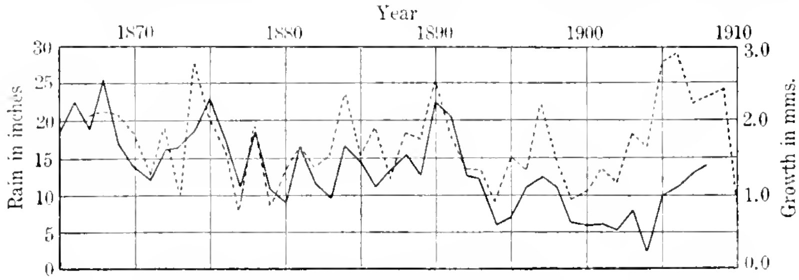


FIG. 10.—Annual Rainfall and Growth of Trees (Group V) at Prescott.
Dotted line = Rainfall. Solid line = Growth.

The final curves resulting from the process described above are given in figure 9. The upper four curves represent the amount of growth year by year of each of the four groups mentioned above. The lower curve shows the mean of all four groups. It will be seen that on the whole these four groups from different localities, 10 miles or so apart, agree quite closely. Nevertheless, as has already been said, the trees of the group nearest to Prescott agree most closely with the rainfall at that place. Accordingly, their growth has been plotted in figure 10, together with the rainfall at Prescott. On the whole there is much agreement, as may be seen by comparing the crests and troughs of one with those of the other. The most conspicuous discrepancy is in 1886, where the rainfall decreases and the growth of the trees increases. In 1873 the growth seems to have responded to the decrease in rainfall, but to a greatly diminished degree. The tree maximum of 1875, one year behind the extreme maximum of 1874 in the rainfall, is entirely reasonable, since the ground may become so saturated that the effects last until the following year. The general falling off of the tree curve during the last twenty years will be discussed later; it is due merely to the fact that the trees grow slowly in old age. On the whole, the curves shown in both figures 9 and 10 support the idea not only of the similarity of the rings of a given year in different trees, but of a proportional relation between annual rainfall and annual growth.

The conclusions regarding yearly identity drawn from the curves at Prescott are supported by those of Flagstaff. In addition to the 25 sections procured there in 1904, 7 others were procured in 1911. The pieces for examination were not cut horizontally as hitherto, but were secured by making two slanting saw-cuts at right angles to one another on the top of the stump, thus bringing away a triangular pyramid of wood, which included the outer 50 to 100 rings. These cuttings were for the purpose of checking the growth in the last half century but made no pretense of reaching the center of the trees, whose average age was three or four hundred years. Figure 11 shows how well the 7 cuttings of

1911 agree with the 25 cuttings of 1904–06. The 7 came from about 12 miles southeast of the town, while the 25 came from places from 6 to 12 miles farther west. The general form of the two curves is strikingly similar, just as is the general form for the four groups at Prescott, as shown in figure 9. This similarity indicates that even a small group of trees, no more than seven in number, is sufficient to give results of considerable accuracy. Indeed, we may go farther and say that a single tree may give results of moderate accuracy provided it grows fast enough, and provided allowance be made for the cumulative effect of a series of good or bad years and for the vagaries due to the age or special position of the

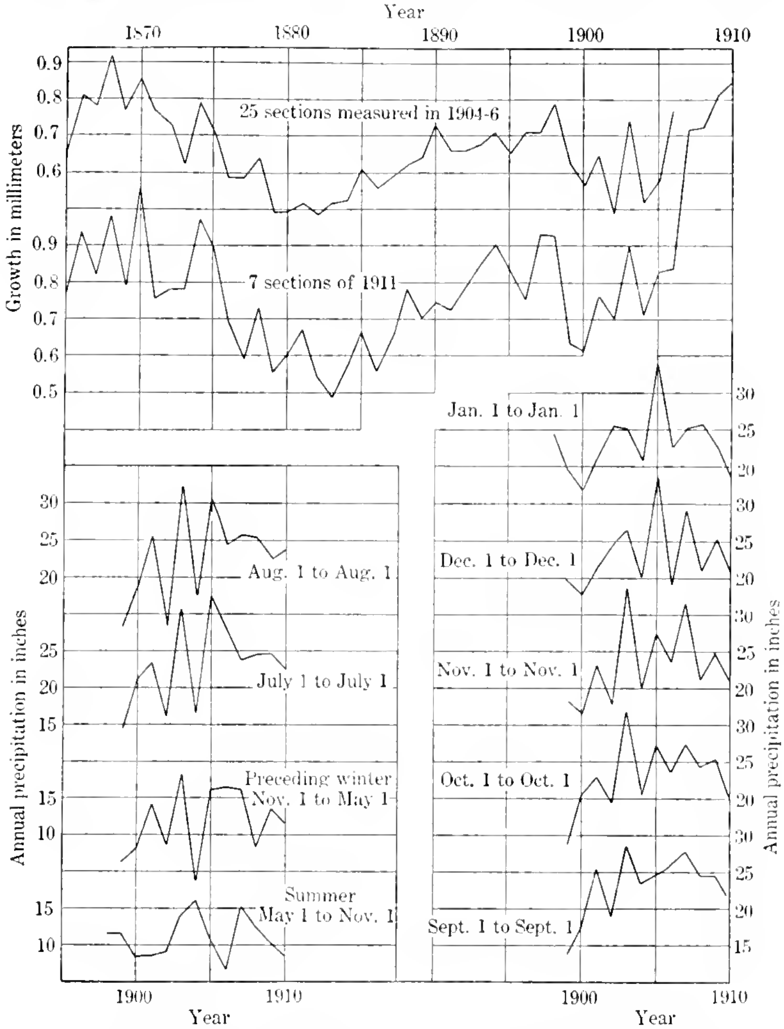


FIG. 11.—Annual Growth of Trees at Flagstaff, and Variations in Annual Rainfall according to Month which is reckoned as the Beginning of the Year.

tree. This is evident in figure 12, where the 7 sections from the last Flagstaff group are plotted separately, the most rapid grower at the top, just below the rainfall curve, and the slowest grower at the bottom. All alike rise because the conditions of rainfall in 1900–10 were more favorable than in 1890–1900, and all, but especially the curve of section 4, show a more or less close relation to the curve of rainfall at Flagstaff, even though that place was some 12 miles away. The great sinuosity of the curve of section 4 as compared with section 5, at the bottom, is noteworthy, for section 4 was cut from a fast-growing tree. This difference supports the conclusion already reached, that slow-growing trees are of less value than rapidly growing ones in the study of the climate of the past.

MONTH OF BEGINNING ANNUAL MEANS.

Before passing on to other matters, a word of explanation must be added as to the method of calculating the rainfall. That it must take some time for the transmutation of rain into an important part of the organic tissue is evident. It has often been asked of the writer how soon the rains affect the trees. There is evidence, as will be shown later, that the summer rains often have an almost immediate effect. The winter precipitation, however, is more remote in its action. Much of the first growth in the spring must come from precipitation long past, and a large part of the yearly growth comes from the melting of the fall and winter snows. It seems reasonable, therefore, to consider any snowfall as applying to the following yearly ring.

At Flagstaff the precipitation of November is almost always in the form of snow, and therefore that month should certainly be considered as falling after the arboreal new year of that locality. In view of the uncertainty as to the exact month when the precipitation begins to have an influence upon the growth of the following season, and in view of probable variations in different years, it seemed wise to test the matter by a purely empirical method. The annual rainfall was ascertained for yearly periods beginning (1) with July 1 of the preceding year, (2) with August 1, and so on to (9) with March 1 of the current year. Another method involved a separating of the summer rains, one-half to apply on each adjacent winter, while a final method involved a similar division of the winter rains. This was done for 12 years at Flagstaff and 43 at Prescott. Part of the Flagstaff curves are given in the lower part of figure 11, where the rainfall can be compared with the growth of the trees. The 11 curves plotted from these figures were found to have substantial disagreements, although, of course, the smoothed curves of all of them would be practically identical. A comparison of the growth of the tree with these 11 curves showed that the use of the year beginning November 1 at Flagstaff and September 1 at Prescott gave the closest agreement between growth and rainfall. At Flagstaff the majority of the trees came from a thin clay derived from decomposed lava, and so there was little depth for the storage of moisture. At Prescott half the sections of group 5, whose curve, it will be remembered, is shown in figure 10, came from trees growing in a porous soil of decomposed granite in a rather flat depression with retarded drainage, so that conservation would have a greater influence. Perhaps this explains why the year beginning September 1 gives the best results there.

THE TIME OF YEAR OF RING FORMATION.

Among the problems connected with the relation of the growth of trees and the amount of rainfall, one of the most interesting was suggested by Mr. R. H. Forbes, of the Arizona Experiment Station. The problem is to determine the time of formation of the red or autumn portion of the rings, and the causes for the formation of double rings. Apparently the red cells are due ultimately to a decreasing absorption of moisture during the cold period of winter when the ground is frozen. This study is the more necessary because many rings in the Prescott series (although very few in the Flagstaff series) show a faint, preliminary red ring forming a double. The first test was designed to determine the character of the rainfall in the years producing such double rings. The half-dozen most persistent cases were selected, and in each of these the red ring was found double in the following number of cases: 4 out of 10 in 1896; 5 out of 10 in 1891; 7 out of 10 in 1881; 4 out of 10 in 1878, 1872, and 1871. The average width of all the rings was 1.55 mm. The mean rainfall by months for the years above selected was found and is plotted in the solid line of the upper diagram of figure 13. Six other rings showing one double in ten trees in 1898, but no doubles in 1897, 1885, 1884, 1876, and 1874, and averaging 1.54 mm. in thickness, were then selected and the curve of rainfall by months for the year during which they grew has been plotted as the upper dotted line in figure 13. The curves seem to indicate clearly that the chief cause of doubling is a deficiency of snowfall in the winter months, December to March. This appears to mean that if the winter precipitation is sufficient to bridge over the usual spring drought, the growth continues evenly through the year, giving a large single ring which ends only in the usual red growth as the severity of winter comes on. If, however, the preceding winter precipitation has not been entirely adequate, the spring drought taxes the resources of the tree and some red tissue is formed because of deficient absorption in the early summer before the rains begin.

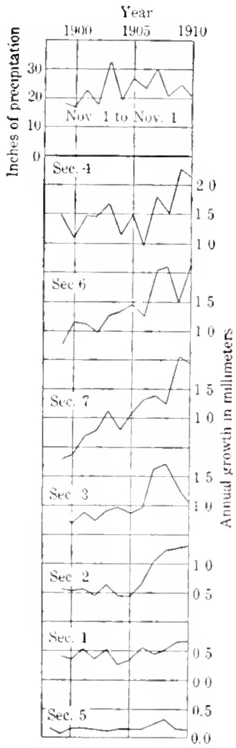
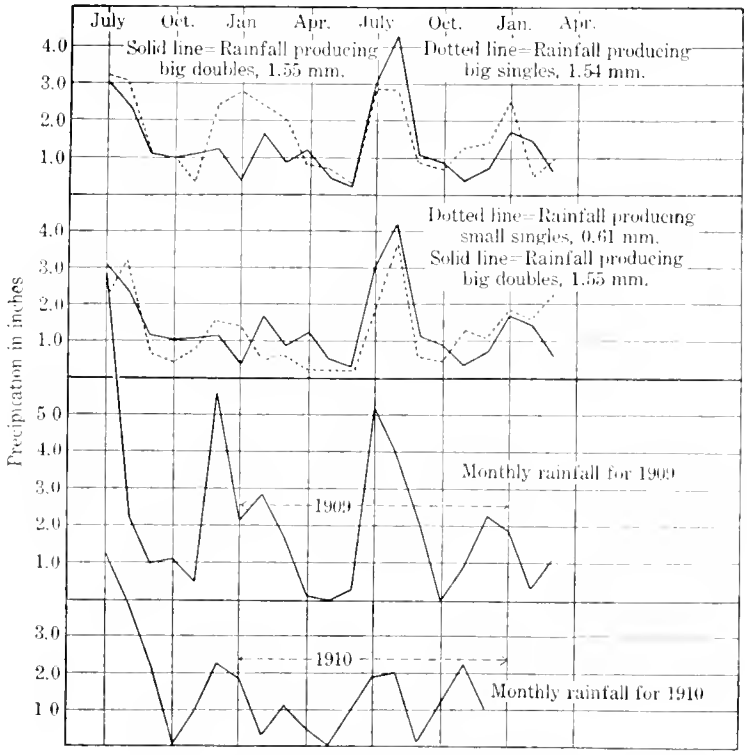


Fig. 12.—Growth of Individual Trees compared with Precipitation at Flagstaff.



Figs. 13 and 14.—Effect of Monthly Distribution of Precipitation on Thickness of Rings of Growth.

It appears further that if not only the winter snows are lacking, but the spring rains are unusually scanty, then the tree may close up shop for the year and produce its final red tissue in midsummer, gaining no immediate benefit from the summer rains. This appears to be the interpretation of the lower diagram of figure 13. Here the same 6 big doubles mentioned above are plotted, together with a selected list of 6 small singles particularly deficient in red tissues. They are 1904 (double once in ten), 1902 (double once in ten), 1899 (single), 1895 (single), 1894 (single) and 1880 (double once in ten). In these it is evident that drought in the spring stops the growth of the tree. The double ring therefore seems to be an intermediate form between the large, normal, single ring, growing through the year, and the small, deficient ring, ending its growth by midsummer. This probably explains why the Prescott trees do not show an agreement of more than about 70 per cent between growth and rainfall. It suggests also that the Flagstaff trees which grow under the conditions of more rainfall, and which have very few double rings, give a more accurate record than those of Prescott. Consistent with this view of the doubling is the condition of the outer rings in the various Prescott groups collected by Mr. Hinderer. These trees were cut during various months from May to November. Naturally those cut in May are in the midst of their most rapid growth, while those cut in summer may or may not show the double ring just forming. The conditions are shown in table 2.

TABLE 2.

Group.	Date of cutting.	Season.	Altitude.	Remarks.
1	1911	May, June...	6125	9 out of 10 show white tissue only, indicating rapid growth.
2 and 4	1909	July to Sept..	6420	30 out of 33 show red ring just forming; this is probably a doubling.
5	1909	Summer......	5800	3 or 4 out of 10 show red ring just forming; probably a double.
3	1910	Oct. and Nov.	6800	All 12 show white without red; probably a large single.

By reference to figure 14, showing the curves of monthly rainfall for 1909 and 1910, it will be seen that 1910 would be likely to carry its growth right through the year and produce a single line, as in group 3 above. 1909 is of intermediate character, having heavy winter precipitation and also a severe spring drought of 3 months. So in the groups cut at this time 33 out of 43 show a red ring forming in July, August, or September, doubtless the preliminary ring of a double. This lesser red ring is due to the spring drought,

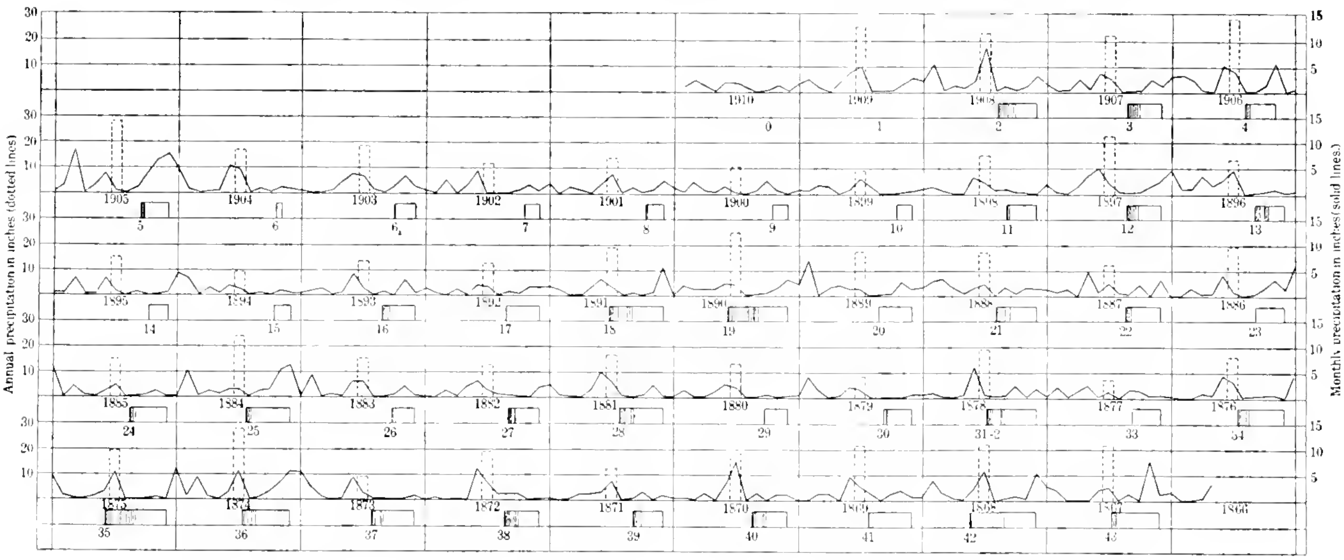


FIG. 15.—Monthly and Yearly Precipitation from 1866 to 1909, and Size and Character of Rings.

and its appearance at this time indicates a lag of a couple of months, more or less, in the response of the tree to rain. The whole matter of the relative thickness of the red and white portions of the rings is illustrated in figure 15. The heavy, sinuous line shows the rainfall month by month at Prescott throughout the 43 years under consideration. The total rainfall for the year is indicated by the dotted rectangles, while the size and character of the rings is shown in the solid rectangles. In these the white portion indicates white tissue and the shaded portion indicates red tissue.

MATHEMATICAL RELATION OF RAINFALL AND GROWTH.

All the preceding investigations lead up to the question of the accuracy with which the growth of trees represents the rainfall. The final answer will necessarily require a large amount of work, but even now some definite idea may be obtained. In order to answer this question an effort was made to construct a mathematical formula for calculating the annual growth of trees when the rainfall is known. Any such formula must perform three principal functions: first, it must reduce the mean rainfall to the mean tree growth; second, it must provide a correction to offset the increasing age of the tree; and, third, it must express the degree of conservation by which the rain of any one year has an influence for several years. In a formula of universal application, other factors will play a part, but for a limited group of trees in one locality they can be neglected. In calculating the

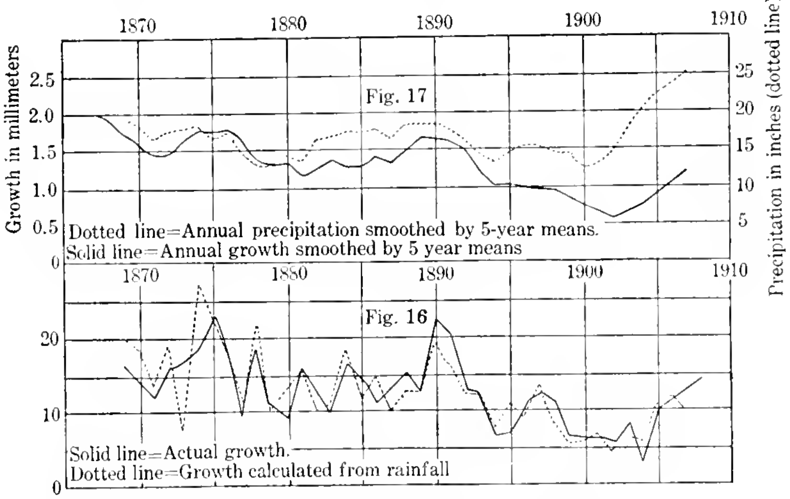


Fig. 16.—Actual Tree Growth Compared with Growth Calculated from Rainfall.
Fig. 17.—Five-year Smoothed Curves of Rainfall and Tree Growth at Prescott.

formula, the group of ten trees nearest Prescott was used. The first process, namely, the reduction of the mean rainfall to the mean tree growth, was easily accomplished. Expressed in actual figures, the rainfall was about 250 times the average thickness of the rings. This is the general factor K in the formula on the next page.

The second process, namely, the correction for the age of the tree, was practically omitted in forming the curves here shown, since, judging by the Flagstaff curves, its effect would be very slight in the interval under discussion. In long periods it is an immensely important correction and its effect should always be investigated.*

The third process, that is, the calculation of the effect of conservation, is far more complicated than the others and its results may be regarded as provisional until a large number of further investigations have been made; yet already very promising results have been obtained, which give an agreement of more than 80 per cent between the calculated curve and the curve derived from actual measurements, as is shown in figure 16.

There are two features of the conservation factor worth calling attention to: (1) that in this dry climate it applies better as a coefficient than as an additive term (while there is evidence, as given in a later chapter, that the additive form is better in a moist climate), and (2) that it gives a prominent place to "accumulated moisture" as commonly used in meteorology. Accumulated moisture is simply the algebraic sum of the amounts by which

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* Over short periods the change may be regarded as linear and a convenient formula is $\frac{g_n}{g_y} = 1 - k(n - y)$, where g_n = growth in any year n; g_y = growth in middle year of series, and k = a constant, which was 0.0043 in the Flagstaff series; in this form it may be used in the general formula.

In the Flagstaff curves from 1700 to 1900 the growth proved to be inversely proportional to the square root of the time elapsed since the year 1690, and is closely expressed in millimeters by the formula: $T_n = \frac{10}{\sqrt{n - 1690}}$.

T_n is here the tree growth for the year under discussion.

If G be the mean size of ring, then the factor to be introduced in a general formula becomes $\frac{10}{G\sqrt{n - 1690}}$.

all the years in a series from the start to and including the year desired depart from the mean. It may be expressed by a formula, thus

$$A_n = (R_n - M) + (R_{n-1} - M) + \cdots (R_1 - M) = R_n + R_{n-1} + R_{n-2} + \cdots R_1 - nM$$

and conversely

$$R_n = M + A_n - A_{n-1}$$

In this formula, A_n is the accumulated moisture for the nth year of a series of consecutive years whose mean rainfall is M, R_n is the rainfall for that nth year, and R_{n-1} is the rainfall of the next preceding year, and so forth.

Now the accumulated moisture curve for Prescott, when brought to proper scale, almost coincides with the smoothed curve of tree growth: hence the relation of the smoothed curve of rain (individual years vary too much) to the accumulation curve represents very successfully the temporary relation between rainfall and tree growth and it is only necessary to change the annual rain in the same proportion to produce the tree growth, as appears in figure 17. The smoothed curve of rain in this case consisted of successive or overlapping 5-year means used in the place of the middle or third year. For example, the average rain of 1881 to 1885 was placed in 1883, the average of 1882 to 1886 was placed in 1884, and so forth. Its formula appears thus:

$$S_n = \tfrac{1}{5}(R_{n-2} + R_{n-1} + R_n + R_{n+1} + R_{n+2})$$

The simple empirical formula for the tree growth, T, for the nth year of this series thus was found to be:

$$T_n = K \cdot \frac{cM + dA_n}{S_n} \cdot R_n$$

in which c and d are small constants found advantageous in reducing the accumulated moisture curve to proper scale. In actual numbers this becomes

$$T_n \text{ (in inches)} = \frac{1}{250} \cdot \frac{0.90M + \frac{1}{4}A_n}{S_n} \cdot R_n \text{ (in inches)}$$

The mean value of the rainfall, M, is 17.1 inches.

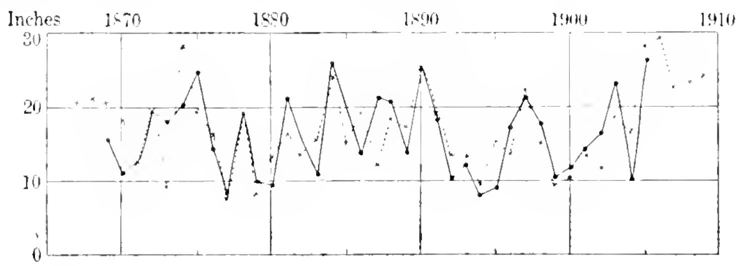


FIG. 18.—Actual Rainfall Compared with Rainfall Calculated from Growth of Trees, Arizona.

- - - = Observed rain. ——— = Rain calculated from trees.

The reversal of the process in order to ascertain rainfall from tree growth seems to be fully as accurate over this limited period and its result is shown in figure 18, where the curve has an average accuracy of 82 per cent for individual years. In producing this reversal the following operations were performed:

1. A 5-year smoothed curve was made of the tree growth (expressed in millimeters). This gives us the term $\frac{3.6M + A_n}{250 \cdot 4}$ in the reversed formula $R_n = \frac{S_n}{\frac{3.6M + A_n}{250 \cdot 4}} \cdot T_n$
2. This term is multiplied by 1,000, reduced to inches, and $3.6M$ subtracted, leaving A_n in inches.
3. From A_n, an approximate R_n is found by the formula $R_n = M + A_n - A_{n-1}$
4. This series of approximate rainfall, R_n, is smoothed and becomes the S_n of the formula.
5. Final values are then found by the proportion: $\frac{3.6M + A_n}{250 \cdot 4} : S_n :: T_n : R_n$

It should be emphasized that the above formula for conservation is the one found to apply under dry climatic conditions. In moist climates the trees, so far as observed, seem to depend on other meteorological elements or combination of elements.

The Prescott trees, as we have seen, even without correction, give a record of rainfall with an accuracy of about 70 per cent. It is likely that the Flagstaff trees, with their higher elevation, more certain rainfall, and more central location in the zone occupied by this species, give somewhat more accurate records. They are probably much less often subjected to extremes of dryness which throw the tree out of its equilibrium, and cause it to produce an abnormally small set of rings. It seems likely, also, that the less porous and less conservative soil, combined with a more abundant precipitation, produces a yearly growth more nearly proportional to the rainfall than at Prescott.

THE FLAGSTAFF 500-YEAR CURVES.

Previously in this chapter, we have endeavored to determine the exact relation between growth and rainfall and to ascertain the most accurate method of obtaining results. We shall now apply these conclusions and methods to the oldest available trees. For this purpose 19 of the Flagstaff sections were selected and were subjected to minute examination and cross identification, in order, so far as possible, to eliminate all errors due to the omission or doubling of rings. For convenience in handling the sections, each one was reduced to a strip of wood extending from center to bark. The best of these was adopted as a standard. It was then compared with each of the others, ring for ring, for 300 years. In this long period only 9 years required a second examination, and only one required a third. This was the ring for 1821, which was often merged with that for 1822. The 2 rings appear as one in 10 sections and as 2 in only 9 sections, but in many or most of the cases where 2 appear, they were so distinctly separate that they were counted as representing 2 years. This is not aboslutely certain, however, and thus there may be an error of one year in the portions of the curve of growth before 1821.* So far as is known, there is no probability of any other error. In order to show the value of cross-identifying the rings of one tree with those of another, Table J has been inserted on page 330 of this volume. It shows the errors of identification in the original measurements of 1906, when the same sections were reviewed in the light of later knowledge. The table shows the exact errors made in the original, straight-away counting, both in the number and place of the rings. It is published here, partly, because it corrects the various errors in the sections of corresponding number as they appear in the Monthly Weather Review for June 1909.

In studies like the present, it is manifestly desirable to carry the curves of growth as far back as possible. Only a few trees go back to an age of over 300 or 400 years, but

* Subsequent comparison with historical records supports the identification here adopted. The data, however, were not obtained in time to be incorporated in this volume.

these are enough to give approximately correct results, although greater accuracy is of course highly desirable. In order to test the degree of accuracy to be obtained from a small number of trees, a comparison was made between large groups and small. After the entire group of rings in each section, some 6,300 in all, had been identified and numbered, the sections were tabulated in order of age, with the oldest first. They were then separated into groups of five, and in a convenient manner averages were obtained of the oldest five, going back about 400 years; the oldest ten, 350 years; the oldest fifteen, 300 years, and the entire nineteen reaching back only 200 years. Finally, at the ancient end of the oldest five, the oldest two were carried back to fully 500 years. On plotting the groups

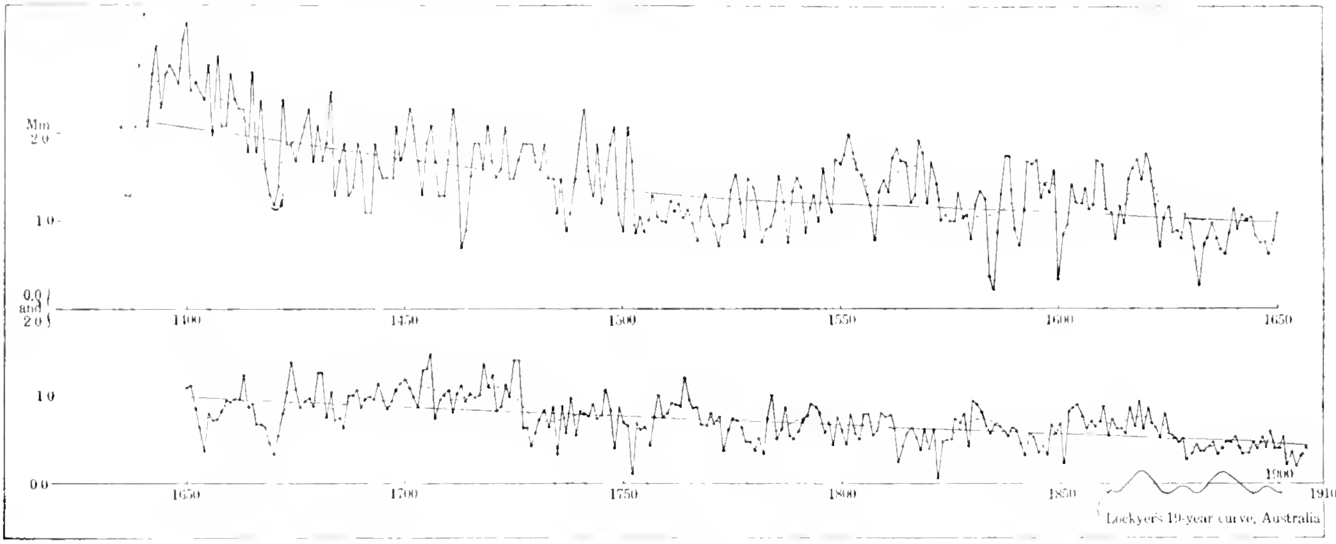


FIG. 19.—Annual Growth of Trees at Flagstaff since 1385 A. D.

of fifteen, ten, and five with its extension of two, it became immediately evident that five trees gave almost the same growth as fifteen, even to small details. So in the work discussed below, the five are used to give the record from 1503 to 1908; so also for the same reason a comparison was made between these five, and the two oldest taken by themselves. In this the agreement was not quite so perfect, yet was so close that errors thus introduced will not at all affect the curves referred to below. However, the two oldest were very slow growers, and 5 mm. were added to all their records where only these two were used, in order to make their curve continuous with that of the whole five. Thus the tree record is made to extend from 1411 to 1908, as is shown in figure 19. Unfortunately, it must not be taken for granted that this remarkable agreement between very small groups of trees is true necessarily for other trees, or even for this yellow pine tree under all conditions. It is without doubt due to the fact that this tree under semi-arid conditions is extremely sensitive to varying moisture supply.

This extreme sensitiveness causes one fault in the record, namely, the frequent omission of rings between 1891 and 1896, as is evident in the list already given; the complete omission of a ring is an exaggeration which should be guarded against. Accordingly, these years were specially investigated in both rapid-growing and slow-growing trees, and a series of growth values estimated from the trees which did not omit the rings. These interpolated values have been used in the figure.

As has already been said, a correction is needed to offset the faster growth of trees in youth than in old age. This has been made empirically by drawing a long, nearly straight line throughout the plotted curve for 500 years. The slope in this line shows very closely the change in growth with advancing age. Long, slow variations in the rate of growth may not cause any divergence from the line, but brief periodic departures are manifest and may be taken as truly representing the extent to which the climate departs from the mean. The departures, however, are not all on the same scale, for where the growth is large, the departures are large, and vice versa. Hence, they must all be reduced to the same scale. This reduction has been effected by dividing the numbers used in figure 19 by the reading of the long, straight line in millimeters for the corresponding year. By this process a series of values of tree growth is obtained such as the trees would give if they grew on the average a millimeter per year and did not change with age.

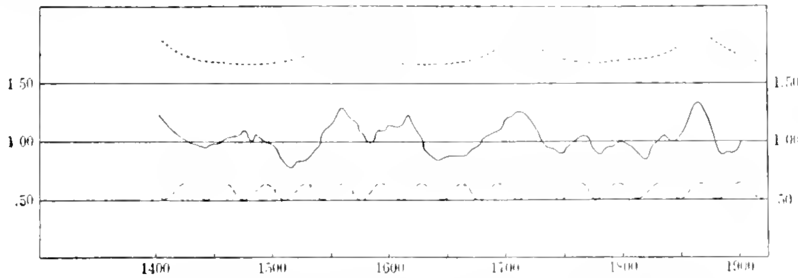


FIG. 20.—500-year Curve of Tree Growth—20-year Means.

CLIMATIC CYCLES.

In the corrected curve of growth thus obtained the minor deviations obscure the larger features. Accordingly, in figure 20 the curve has been condensed into a 20-year smoothed curve. This particular length of time was chosen because a 21-year variation is evident in most of figure 19, and this, as well as smaller variations, must be removed in order to leave larger variations unaffected. A 20-year smoothed mean accomplishes the desired result and is easier to calculate than is a 21-year mean. Inspection of the curve of figure 20 shows a long and pronounced maximum of tree-growth between 1530 and 1620, a lesser maximum shortly after 1700, and a still shorter one at about 1860. Strong minima occur between 1505 and 1530, 1630 and 1675, here and there between 1740 and 1830, and again between 1870 and 1900. Manifestly pulsations of some sort take place. They may or may not be permanent. Perhaps they are nothing more enduring than a series of simultaneous wave systems on a water surface. Yet for the navigator a knowledge of the existing system is important; and so for the purpose of weather prediction we need to know the nature of the pulsations now existing, and each one should be minutely studied. The slow changes shown in the curve seem to have a somewhat regular periodicity. In order to bring this out, a wavy line representing a cycle of 150 years has been placed above the curve of growth. This cycle in the growth of the trees is fairly well evident, and it is represented again in figure 21, where the three cycles shown in the main line of figure 20

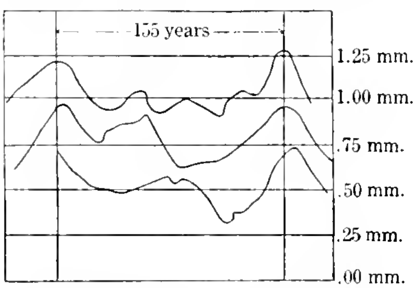


FIG. 21.—A Possible 150-year Period.

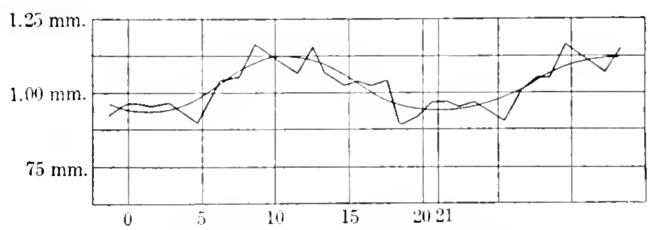


FIG. 22.—Mean Curve of the 21-year Cycle.

have been placed, one above another, instead of consecutively. A cycle of this length is interesting, not only in itself, but because it is one-half of the period which Clough thinks that he has discovered.* The lower wavy line in figure 20, representing a cycle of 33.8 years, agrees with a cycle of similar length in the curve of growth for the last 180 years, but in the years preceding that time no such cycle is apparent. On the whole, then, the growth of these trees seems to indicate that a cycle of this length is not here a permanent feature. This is important because of the large amount of discussion in regard to the 35-year cycle of Brückner.

In his "Discussion of Australian Meteorology" (South Kensington Solar Physics Observatory, 1909), Dr. W. J. S. Lockyer finds a pronounced 19-year cycle in barometric

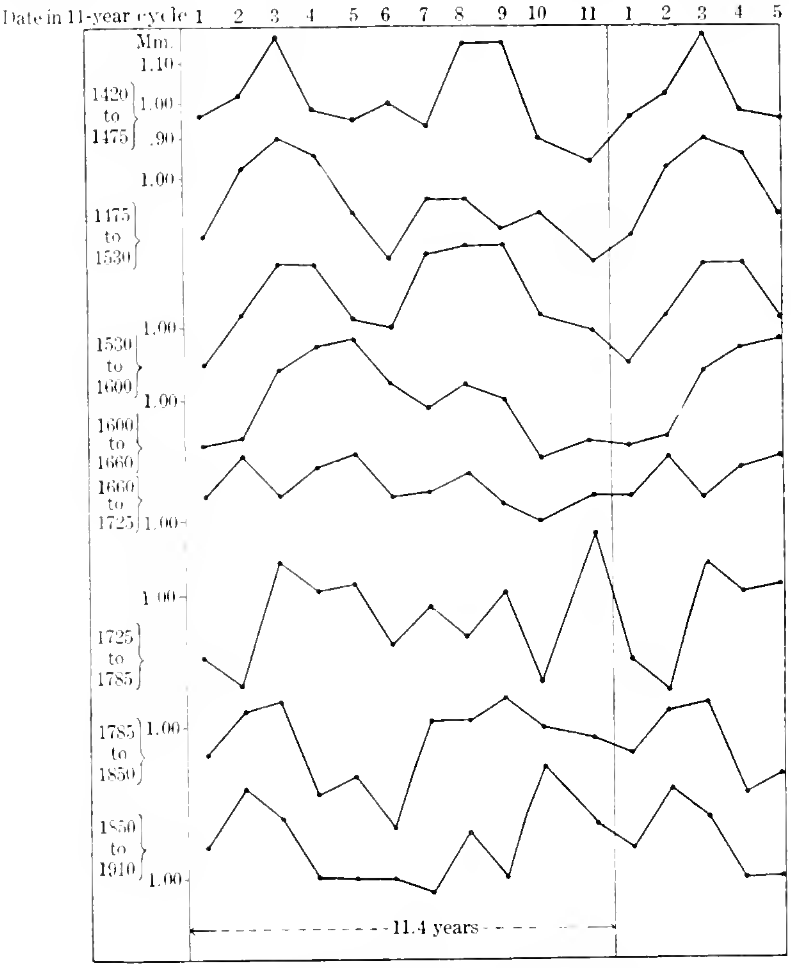


FIG. 23.—Variations of the 11-year Cycle.

pressures exhibited in Australia and South America. A year or two before Lockyer's publication, I had worked out a distinct period in the northern Arizona trees, which at first seemed to be 19 years, but on close analysis proved to be 21 years. With all the improvements of method now made, this variation is evident for more than 400 out of the 500 years and its length is 21.0 years. For a great majority of the time the crests and troughs follow each other with great regularity. On the average the total variation is 20 per cent of the mean (see figures 19 and 22). When this variation is plotted it shows a

* H. W. Clough: Synchronous Variations in Solar and Terrestrial Phenomena. Astroph. Jour., pp. 22-42, 1905.

very regular curve, but with three subordinate minima dividing the whole into three equal parts; this secondary cycle seems likely to be due to traces of the 11-year period now to be mentioned.

The last cycle to be considered is that of 11 years. In the 60 years during which the 11-year sun-spot and magnetic cycle has been recognized, this period has been of the greatest interest, for it deals with a connection between the sun and the earth other than gravity which holds the earth in place, and it indicates that the energy given out by our great central luminary is not constant. Since 1873 many writers have found variations in the ordinary meteorological elements, rainfall, temperature, and pressure corresponding to this period. Hence it is of peculiar interest to see whether the trees which carry the rainfall record back so far with a comparatively high degree of accuracy show the same cycle. In nearly all parts of the long, 500-year curve, there are suggestions of an 11-year variation. By tracing this throughout the record, the period is found to have a length of very nearly 11.4 years, which is sufficiently close to the length of the sun-spot cycle to be considered identical with it. The average total variation is 16 per cent of the mean. The average conditions of growth during eight different intervals of approximately 60 years each are shown in figure 23. From this it appears that the 11-year cycle is not uniform throughout the whole period of 492 years covered by the curve. In general the cycle shows two maxima and two minima. From 1400 to about 1670 the second minimum is generally the deeper. Then from about 1670 to about 1790 the cycle flattens out, and has no marked rhythmic character. From about 1790 to the present time there are again two minima, but here the first is, on the whole, more conspicuous.

The average of all the 11-year periods from 1492 to the present time is shown in the upper curve of figure 24. Below this is the rainfall for 50 years on the California Coast,

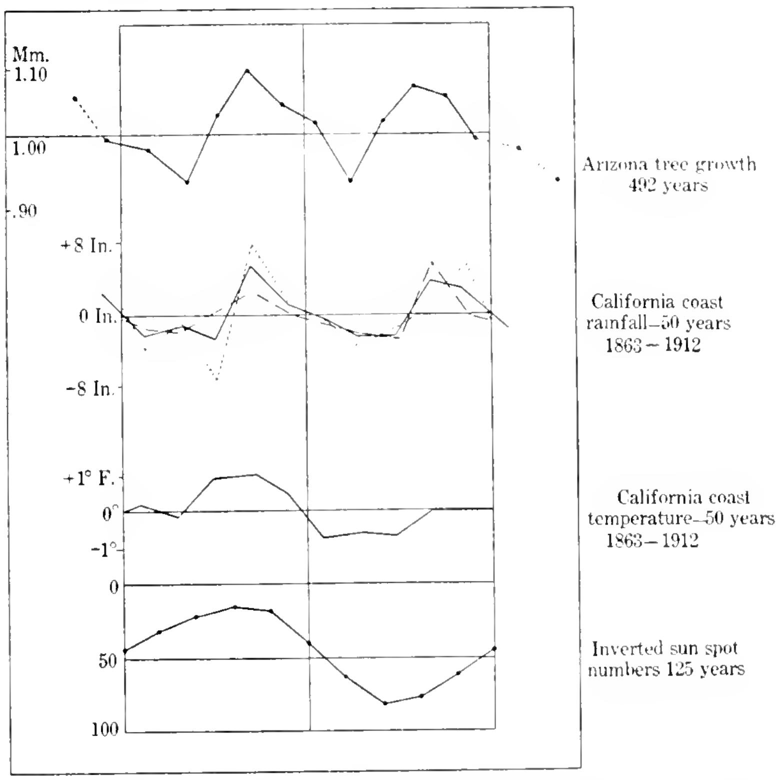


FIG. 24.—Comparison of 11.4-year Cycles in Tree Growth, Rainfall, Temperature, and Inverted Sun-spot Numbers.

the dotted line representing San Francisco, the dot and dash line San Diego, and the solid line the mean of these two. These have been averaged in 11-year periods, just as have the measures of tree growth. Although this coast is 500 miles distant from the Arizona trees, and lies beyond the mountains, yet the crests and troughs of the tree growth in Arizona correspond closely to those of the rainfall in California. This is not surprising, for while the summer rains of northern Arizona have no relation to the coast of California, the winter precipitation in the two regions varies in harmony. Below the rainfall curve is placed another, showing the average temperature at San Diego during the 11-year periods of the last 50 years. Shorter curves of temperature of other towns of the California coast show the same characteristics as that of San Diego. Here we find in the first half a marked similarity to the rainfall curve, especially to that of San Diego. In the second half, however, the temperature curve finds the minimum satisfactorily, but partially fails to rise to the maximum. Thus in that coast region we find exemplified in the 11-year period a change from a two-crested cycle of rain to a one-crested cycle of temperature. This is not new, for it happens every year in Arizona. That State has a double rainy season, winter and summer, giving, therefore, a yearly rainfall curve with two crests. But its temperature curve, of course, has a high summer crest only. One maximum of rain corresponds to a maximum of temperature, but the other maximum of rain corresponds to a minimum of temperature. Dr. Lockyer has worked out a similar transition from precipitation to pressure in Australia, and doubtless it exists in other subtropical regions, and probably in other cycles. The present case shows that it extends outside annual variation.

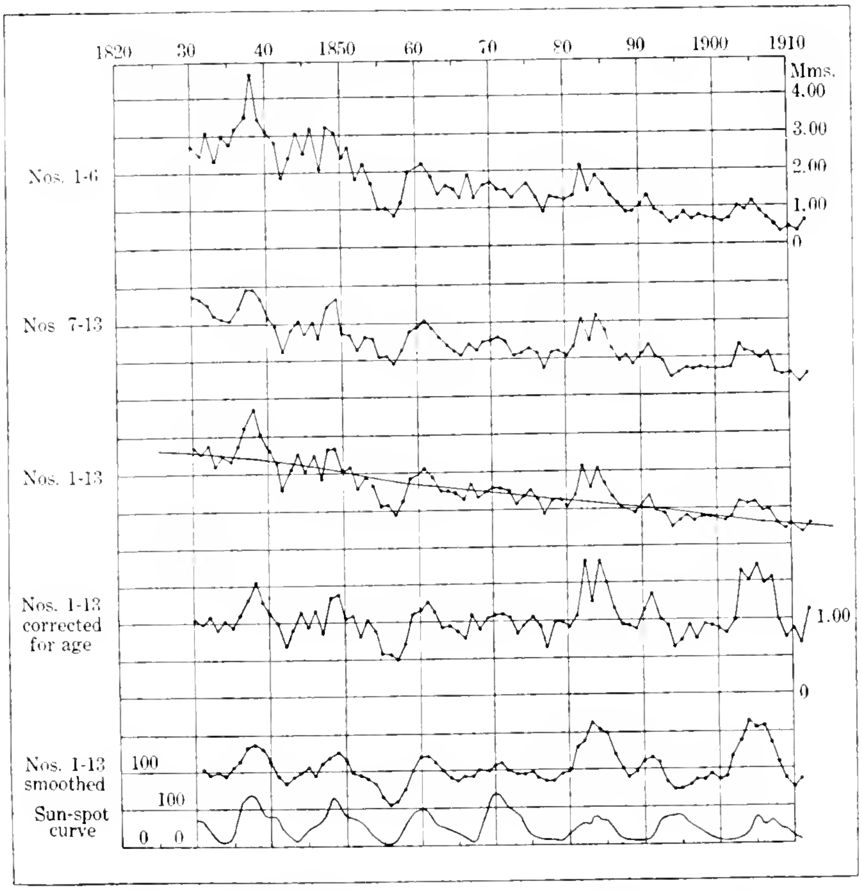


Fig. 25.—Sun-spots and the Growth of Trees at Eberswalde, Germany.

The lowest curve is an inverted sun-spot curve for 125 years, 1771 to 1896. There appears to be a marked similarity between this and the temperature curve. Even the subordinate crest, which sometimes shows in the sun-spot descent from maximum to minimum, matches this suppressed second crest of temperature and its following faint minimum. This would seem impossible in the absence of a real relationship between them.

The relation between tree growth and sun-spots here shown, however it comes about, does not stand alone. A series of measures on 13 tree sections from the forest of Eberswalde, near Berlin, Germany, the first of a number of series to be made on North European pine trees, discloses a striking time relation of the same character. The 13 trees were divided into two subordinate groups, given in curves 1 and 2 of figure 25. These show most satisfactory agreement. The third curve gives the growth of the whole 13. The fourth curve is the same as the third, but corrected for age. The fifth curve shows the tree growth smoothed in overlapping groups of three, and below it is the sun-spot curve. The similarity may be traced without further comment. This gives very strong support to the view here entertained that there is a relationship between the tree growth and the sun-spot activity through the mediation of the weather.

CONCLUSION.

In the foregoing investigation it has been shown: (1) that the variations in the annual rings of individual pine trees in the dry regions of northern Arizona exhibit such uniformity that the rings of one tree can be identified in others over large areas and the date of their formation established with practical certainty; (2) that the ring thicknesses are proportional to the rainfall with an accuracy of 70 to 82 per cent in recent years and that this accuracy presumably extends over centuries; (3) that the tree year for such records begins in the autumn; (4) that double rings are caused by spring drought and are indicative of the distribution of rainfall throughout the year; and (5) that an empirical formula can be made to express the relationship between tree growth and rainfall. The ring record at Flagstaff, Arizona, has been traced back 500 years and various cycles found in it. An approximate 33-year cycle shows in the last 200 years. A 21-year cycle shows in 400 years and an 11-year cycle displays a similar duration. The 11-year cycle shows marked relationship to the California coast rainfall and temperature and to the sun-spot curve. In corroboration, attention is called to the still more remarkable agreement between tree growth in northern Germany and the sun-spot curve. All of this confirms the idea that observation of tree growth may be a powerful help in studying the climate of the past.

Further research will probably show other and perhaps still more important relationships between the growth of vegetation, meteorological elements, and changes in the sun. Meanwhile, the methods of computing rainfall from tree growth must be still further perfected. Already, however, the original purpose of the work here outlined has been accomplished. Its most important part, I hope, has been the establishment of a method of estimating rainfall, capable of extension to other regions, and for the benefit of other branches of science.

CHAPTER XII.

THE CORRECTION AND COMPARISON OF CURVES OF GROWTH.

In making use of the method of tree measurements elaborated in the previous chapter by Professor Douglass, I have employed two sets of data, those of the United States Forest Service and those obtained by my assistants and myself among the giant sequoias or "Big Trees" of the Sierras during two seasons in California. The Forest Service, through the courtesy of the Forester, Mr. Henry S. Graves, kindly put at the disposal of the Carnegie Institution the large body of "stem analyses" which his Bureau has collected from forests in all parts of the country. A stem analysis is simply the record of the measurement of the thickness of the rings of annual growth. The Forest Service makes such analyses at various points along the trunks of trees that have been cut for lumber, but the only ones that have here been used are the "stump analyses," or measurements made directly upon the top of the cut stump. The method employed by the Forest Service is to pick out an average radius, and begin measuring from the outside inward toward the center. A finely graduated ruler is laid upon the stump and from this the distances are read off and recorded in books especially prepared for the purpose. The unit of measurement is 10 years, since it is difficult to measure the individual years without an undue expenditure of time. Moreover, for the purposes of forestry—that is, for determination of the rate of growth of various species under different conditions—a 10-year unit is as good as a smaller one. Only in the case of young trees does the Forest Service employ the year as the unit in stem analyses.

The measurements which I obtained in California were made in the same way as the ordinary stump analyses of the Forest Service, except that in many cases the best radii were chosen instead of the average; these will be discussed fully in the next chapter. At present we shall confine our attention to the measurements made by the Forest Service. We shall consider the two chief ways in which the curves obtained by the simple process of averaging need correction before they give a true idea of the comparative climates of the past and the present, and shall elaborate the method of correcting them, a method which is purely mathematical and does not involve the introduction of the personal equation to any appreciable extent. Then we shall be prepared to inspect the curves and to find out what they indicate as to our main problem. The total number of analyses which were chosen from among the many thousand in the archives of the Forest Service is 2,664. Only those of trees having an age of over 200 years were selected. In the case of many species only a few specimens reach that age, and the number is not large enough to furnish curves sufficiently reliable to be worth publishing. In fifteen cases, however, it has been possible to find enough old trees to justify the construction and publication of their curves. The same method of correction was employed with all of them, except that in some cases one of the two corrective factors, which are to be discussed later, did not seem to apply.

The annual rate of growth of trees is subject to variation for four chief reasons. In the first place, trees grow at very different rates according to their age, young trees usually growing rapidly and old trees slowly. In the second place, trees destined to have a long life usually make haste slowly, being outstripped at first by their neighbors, which are to die much sooner. These two types of variation can be calculated with mathematical precision, and by the use of the proper formulæ corrective factors can be obtained by means of which errors due to them can be largely eliminated. The third reason for variation in the annual rate of growth of trees is the occurrence of non-climatic accidents such as shading in youth, the breaking of branches, the slipping of the soil, the ravages of insects, or the devastation wrought by fire. At first sight these appear to be of almost preponderating importance, but as a matter of fact they play by no means so great a rôle as would be expected, for, as Professor Douglass has shown, two or three trees, or even a single tree, under exceptionally favorable conditions, gives a fairly accurate climatic record but little disturbed by accidents. Finally, the fourth reason for variation is the changing conditions of weather and climate which prevail from year to year. It is these which we wish to determine, and this can be done only by eliminating variations due to the other three causes. Let us therefore turn to the problem of how this elimination is to be accomplished. As accidents are the matter which critics of the method here discussed are most likely to emphasize, let us take them up first.

The elimination of the effect of non-climatic accidents upon the rate of growth of trees is accomplished largely by the process of averaging. If a sufficient number of trees is used, and if the trees are distributed over a wide and varied area, purely individual accidents will disappear by the law of averages. Where a large group of trees is concerned, each year —and still more each decade—is characterized by about the same number of cases of the slipping of the soil, the crashing of one tree into another, the eating of roots or buds by rodents, and the many other little accidents which are continually checking and sometimes stimulating the growth of vegetation. The combined effect of all these accidents is a nearly constant quantity. Assurance that this quantity is actually constant can be obtained only by using a sufficiently large number of measurements distributed over a sufficiently wide area. Another type of accidents, such as the ravages of insects and of fire, can not be gotten rid of quite so easily, since they are more widespread and prevail much more abundantly in some years than in others. Even with these, however, the effect can be reduced to a small amount by means of abundant and widely scattered measurements. Moreover, when the ravages either of insects or of fire are unusually widespread and become regional instead of purely local phenomena, the cause is almost always found in unpropitious conditions of climate. Hence, where the effects of such ravages can not be eliminated, they will only rarely be found to mask the effects of climate or prove opposed to them. As a rule they merely intensify the retardation of growth which normally accompanies times of unfavorable conditions of climate. The case is even stronger than here appears, but I shall defer further discussion of it until we have some actual curves before us and can discuss the matter in relation to them.

The elimination of the differences in rate of growth due to the fact that young trees grow more rapidly than older ones is easily made. A glance at the curves prepared by Professor Douglass and presented in the preceding chapter will show that the earlier portions are much higher than the later parts. This, as is already apparent, does not represent a climatic difference, but is merely due to the fact that trees grow rapidly in their youth. Manifestly allowance must be made for this varying rate of growth. I have called this allowance the "corrective factor for age." The method of obtaining it is illustrated in the accompanying diagram, figure 26. Let the horizontal line represent the course of time as indicated in years by the figures 10, 20, 30, 40, etc. Let the vertical distance indicate the average thickness of the ring of wood added each year. Suppose that we have 100 trees varying in age from 50 to 200 years. Let us suppose further that we have averaged up the rate of growth of all these trees during the first year of their lives and find that it amounts to one-tenth of an inch. In the same way we find that the growth during the tenth year amounts to 0.15 of an inch; during the twentieth year 0.175; during the thirtieth, 0.19; and the fortieth 0.20. After the fortieth year the rate of growth begins to diminish until at the one-hundredth year it has fallen to a figure no larger than that of the first, while at the two-hundredth it has fallen still lower, to 0.05 of an inch. Manifestly it is an easy matter to plot a curve from these figures. The curve will rise rapidly at first, as appears in figure 26, and then will fall more and more slowly. Such a curve, when plotted, will not be perfectly regular, but will be somewhat wavy, as shown in the dotted line, because accidental circumstances, such as shading in youth, or periods of exceptional warmth and moisture and the like, will have caused a very slow or very rapid growth in certain trees at certain times. Nevertheless the variations from a mathematically perfect curve are slight, partly because the number of trees is large enough so that the averages are little affected by accidents to individuals, and partly because of the fact that the first year of one tree may fall 150 years before the first of another, and the rest may be distributed anywhere between these two. Thus the average of any year, whether it be the first, the tenth, or the hundredth, does not represent the climatic conditions of a single year, but of 100 years selected at random. Thus not only the effect of accidents, but also that of climate, is largely eliminated. If we had an infinite number of trees of all ages, even the slight irregularities which now exist would be eliminated and we should obtain a smooth curve like the solid line of figure 26. This would represent the relative rate at which trees of a given species would grow during different parts of their life in the particular locality under consideration, provided that the conditions of sunlight, rainfall, temperature, and soil, as well as the relation of the plant to other vegetation and to accidents, were of the average type and remained constant during the life of the tree.

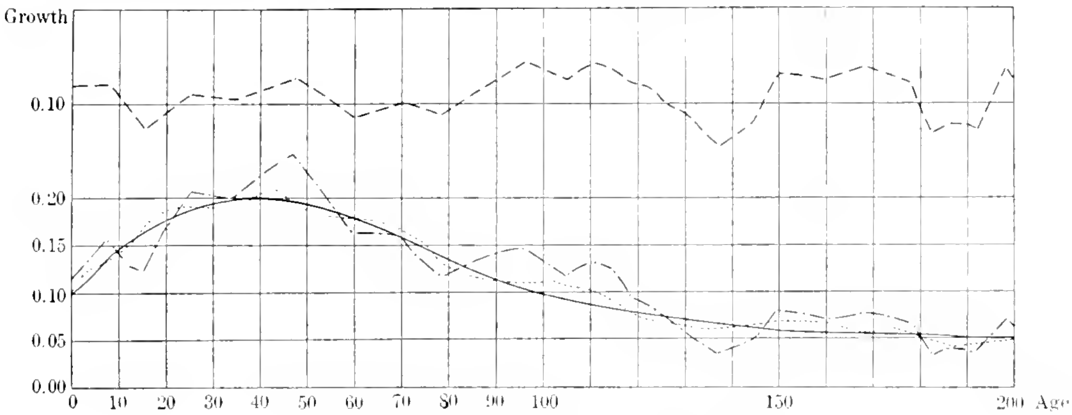


Fig. 26.—Ideal Curves illustrating Correction for Age.

If the curve of growth of an individual tree—the dot-and-dash line, for example, in figure 26—be compared with the ideal smoothed curve, the first feature which strikes the attention is the marked idiosyncrasies, the repeated and irregular ups and downs. So far as these are due to accidents they will be eliminated by averaging, but the majority are due to climatic variations and form the essential object of our investigations. Our purpose is to discover how far a given irregularity in one part of the curve represents climatic conditions like those giving rise to a similar irregularity in another part. A glance at the main features of the curve for an individual tree shows that in its general course from youth to old age it corresponds to the ideal smoothed curve. It is also evident that in the portions of the curve where the tree is growing at the average rate of 0.20 inch per year, an increase of 0.10 inch above the average rate of growth means no more than does an increase of 0.05 where the average rate of growth is 0.10. In both cases the increase amounts to 50 per cent, and it is incumbent upon us to apply a corrective factor in such a way as to cause the two to be reckoned as of the same value. Mathematically this means merely that we must reduce the *smoothed* curve, that is, the solid line of figure 26, to a straight line lying in a horizontal position. This can readily be done by selecting some point as representing the standard or normal growth and then multiplying the value of every other point on the line by a number which will raise or lower the given value to an equality with the value of the point selected as the standard. Manifestly, if all the points on a line have the same value—that is, if they are all at an equal distance from the horizontal base line—the line in question will be straight. Thus the process under discussion reduces the smoothed curve of growth to a straight line. It does not, however, eliminate the irregular idiosyncrasies of the curve of an individual tree, although it changes their relative importance. In the example under consideration the average growth during the first year is 0.10. Let us take this as the standard or normal growth. During the fortieth year the growth is 0.20, or twice as much; to reduce 20 to 10 means simply dividing by 2. Similarly during the two-hundredth year the growth amounts to 0.05; to reduce 0.05 to 0.10 means multiplying by two. In other words, the corrective factor for age during the fortieth year is one-half, or 0.50, while that during the two-hundredth is 2. Having this corrective factor for each year of the tree's life we must apply it to the curves of individual trees. In this way the dot-and-dash line shown in the diagram is reduced to the form shown by the dash line above it. The sinuosities occur at the same time as before, but are less marked than previously during the early years of the tree's growth and more marked during old age, when the tree was growing so slowly that the original curve became very flat. In this final curve the difference in rate of growth between old trees and young has no effect. The variations that remain are due either to accidents, to climate, or to another factor which we shall now consider.

In the original investigation whose results are here being set forth, a puzzling feature appeared when the correction for age was applied to the first three or four species. In the earlier portion of each curve—that is, in the part where only the oldest trees could be used—there was a systematic lowering of position. This appeared to indicate markedly drier conditions in the past than in the present, but the apparent difference was greater than could possibly have existed, and it occurred at different times in different trees, being dependent apparently on the age of that special species. Moreover, it occurred at times when other lines of evidence seem to point to exactly the opposite state of affairs. In attempting to ascertain the cause of this, it was soon discovered that, other things being equal, trees which are destined to live to a ripe old age grow in their youth more slowly than do those of the same species and in the same locality which are destined to die young or to live only until maturity. If the normal life of a species is 200 years, the individuals which are to attain an age or 300 or 400 years, almost without regard to climatic conditions, grow on an average more slowly than do those which in the natural course of events are to die at the age of 200 years or earlier. Slow growth in youth is apparently one of the essential conditions of a prolonged and vigorous old age. This is a well-known fact when different species of trees are compared. The fast-growing horse chestnut does not live to anything like so great an age as the slow-growing oak, but that this same law holds good within the species is not generally realized. It is probably not a universal law, however. Among the conifers whose analyses were obtained from the Forest Service almost all the species show this feature, the only possible exceptions being species for which the data were insufficient to allow of its calculation. Among deciduous trees, on the contrary, judging from the few species yet investigated, there seems to be little difference in the rate of growth of trees which live to be old and of those which die young.

The apparent difference in rates of growth between the old trees and the young ones is by no means a matter of climate or of shelter of the trees during youth. This is proved by the fact that it applies to trees of all ages. That is, it makes no difference whether the average life of the species is 100 or 300 years. In the one case trees which live to be 150 years old are characterized by slow growth in youth, while in the other case the slow-growing trees are those 500 years old. Moreover, in some cases the difference in rate of growth decreases by regular stages. It is most marked in the first decade, less marked in the second, etc., and it commonly disappears or even is reversed by the time the trees attain approximately the average age of maturity. That is, if the ordinary age of a certain species, its "three-score years and ten," is 200 years, the rate of growth of the trees destined to live much longer is, at that time, no less than that of the others, and in many cases more.

Evidently a "correction for longevity" is as necessary as one for age. It is applied in the same way. Figure 27 illustrates the method. The horizontal line in this case indicates groups of trees of a given species. Group (*A*) on the right consists of trees 500 years old, group (*B*) of those 400 years old, (*C*) 300, and so forth. The vertical coordinates represent the amount of growth made by the trees during the first decade. It will be seen that the trees 100 years old made an average growth of 2 inches;

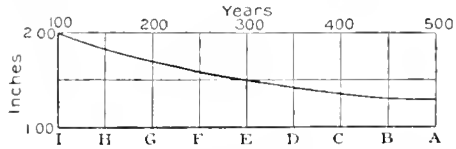


Fig. 27.—Ideal Curve illustrating Correction for Longevity.

those 200 years old, 1.70 inches; 300 years old, 1.50 inches; 400 years old, 1.35 inches; and 500 years old, 1.30 inches.

From this it appears that if the minor fluctuations of climate which took place from year to year during the first decade of the average tree 500 years old are to be compared with those during the corresponding decade of the average tree 200 years old, the growth of the older trees must be multiplied by $1.70 \div 1.30 = 1.31$, the corrective factor for longevity. The process is clearly the same as that of obtaining the corrective factor for age—that is, it consists in multiplying the value of each point of a smoothed ideal curve by a corrective factor which reduces the curve to a straight, horizontal line. The determination of the corrective factor for longevity, however, is more difficult than the determination of that for age, not because the factor for longevity is any less real or is any less strictly a mathematical function, but because more trees are required in order to secure accuracy. Where the number of trees amounts to 200 and the age does not exceed more than 300 or 400 years the factor can be determined with a considerable degree of accuracy. For older trees a larger number of specimens is necessary before high accuracy can be obtained.

In considering both of the corrective factors it must be borne in mind that they are attempts to get rid of all variations except those due to temporary pulsations of climate. The corrections do not and can not take cognizance of any possible changes of climate which may progress uniformly or continuously from beginning to end of the life of the trees in question; they are calculated on the assumption that the average climate of the past was like that of the present. The attempt is to smooth the curves as far as possible and to reduce them as closely as may be to straight lines; the earliest parts are thus brought to the level of the latest in as great a degree as possible. Hence the final curves, while showing all the variations whose periodicity is less than that of the lives of the trees, do not necessarily show long, secular changes which may have taken place. In many cases, to be sure, they appear to show them, the later end of a curve being in general higher or lower than the earlier, but no reliance can be placed on this. It is generally due to errors in applying the corrective factors, and these errors generally arise from insufficiency of data.

In connection with the corrections which have just been discussed, another matter should be considered: The last two centuries of all the curves of growth are based upon a constant number of trees. For earlier dates, the number gradually diminishes, tree after tree being dropped until only a few of the oldest are available. Theoretically the dropping out of tree after tree is an important matter, and may lead to serious errors unless it is guarded against. If at one special period a number of rapidly growing trees happen to drop out, the curve prior to that time will be relatively too low; and, in the same way, if all the trees which began to grow at a given time happen to have grown slowly, the part of the curve before that time will be too high relative to the succeeding part. In order to avoid errors of this sort it would be possible to apply a correction every time that a tree or group of trees is dropped out. In actual practise, however, I have found it inadvisable to attempt this. Where the total number of trees is ten or twenty times as great as the number that is dropped, and where the other corrections have been properly applied, this particular correction makes only slight differences in the general form of the curve.

Unless undue weight is given to the vagaries of a single year, it demands such an amount of calculation that it is not worth attempting.

Turning now from the method of obtaining the corrective factors to their application, let us see how they work in actual practise. Let us take as an example the western yellow pine, the tree used by Professor Douglass, and examine first the curves upon which its corrective factors are based, and then the final corrected curves of growth for the last 300 years. The yellow pines for which data are available fall into two groups: one from the mountains of New Mexico not far from the ruins which were discussed in previous chapters, and one from Idaho. We will begin with those from New Mexico. The figures for all the trees discussed in this chapter, as has already been said, were placed at the disposal of the Carnegie Institution of Washington by the United States Forest Service through the kindness of the Forester, Mr. H. S. Graves. In the case of the yellow pine of New Mexico the Institution is indebted to Mr. A. B. Recknagel, chief of silviculture in the Forest Service at Albuquerque, New Mexico, who not only gathered most of the data, but had them compiled in his office, and placed his results at our disposal. His data, based on 645 trees from four of the United States forest reserves, are shown in table 3.

Table 3.

	Gila.	Jemez.	Datil.	Zuni.	Total.
Over 200 years of age	53	10	74	164	301
Under 200 years of age	124	19	66	135	344
Total	177	29	140	299	645

The Gila and Datil national forests are in the southwestern part of New Mexico near the Arizona line, between the ruins of the Santa Cruz Valley on the west, those of the Animas Valley on the south, and those of the Jarilla Mountains on the east. All three of these groups of ruins are about 150 miles from the center of the Gila forest. The Jemez forest lies in the center of the northern part of New Mexico and adjoins the Pajaritan Plateau, where the ruins of Tuyoni and the Canyon de los Frijoles are situated. The other reserve, the Zuni forest, is in northwestern New Mexico about 80 miles south of the remarkable ruins of the Chaco Canyon and not much over 30 miles from some of the other ruins described in preceding chapters. Thus the forests have approximately the same distribution as the ruins with which we have been dealing, but in general lie at greater altitudes than the ruins. "The measurements," to quote Mr. Recknagel, "were all taken within the western yellow pine type between altitudes of 7,000 and 9,000 feet. They were taken in the main body of the western yellow pine type, and therefore can be considered as belonging to members of the pure stand of the species." In other words, the trees with which we are concerned grew in the portion of the yellow pine area where the trees grow best and where they are neither at the lower limit, so as to be especially liable to injury by drought, nor at the upper limit, so as to be especially liable to injury by excessively low temperature or long winters. In general, the conditions under which the trees grew were practically identical with those described by Professor Douglass at Flagstaff and the higher regions around Prescott. In the selection of the analyses to be used age was the only criterion. All of the

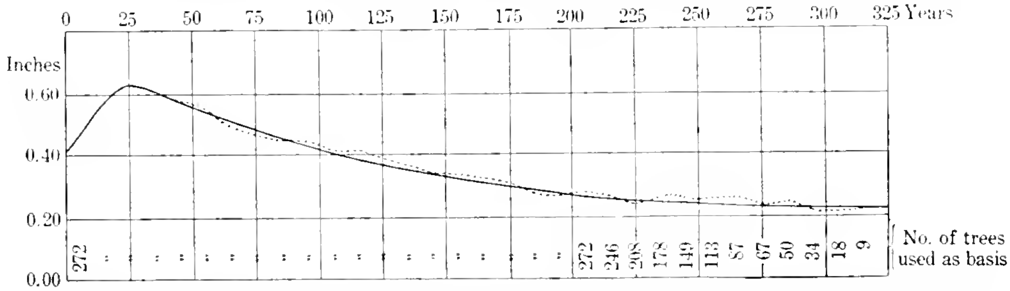


Fig. 28.—Curve of Growth and Correction for Age of Yellow Pine in New Mexico, based on Measurements of 272 Trees computed by Mr. A. B. Recknagel. See Table 3A on page 130.

available analyses of trees over 200 years of age have been used, and to them have been added an approximately equal number of younger trees in order to afford fair comparisons.

The results obtained from the data furnished by Mr. Recknagel are shown in figures 28 and 29. In figure 28 it will be seen that during the first 10 years of their lives the trees on an average grew fairly rapidly, or 0.46 inch for the 10 years. During the next two decades the rate of growth increased rapidly and reached a maximum of 0.63 inch during the third decade. Then it decreased rapidly at first, and then more and more slowly until at old age it had sunk to half of its value when the trees first started. Naturally the original curve, the dotted line of figure 28, shows a certain amount of sinuousity due to the various accidents, climatic and otherwise, to which the 272 trees which it represents have been subjected. In order to obtain the true corrective factor the curve has been smoothed as indicated in the solid line. Table 3A shows the measurement.

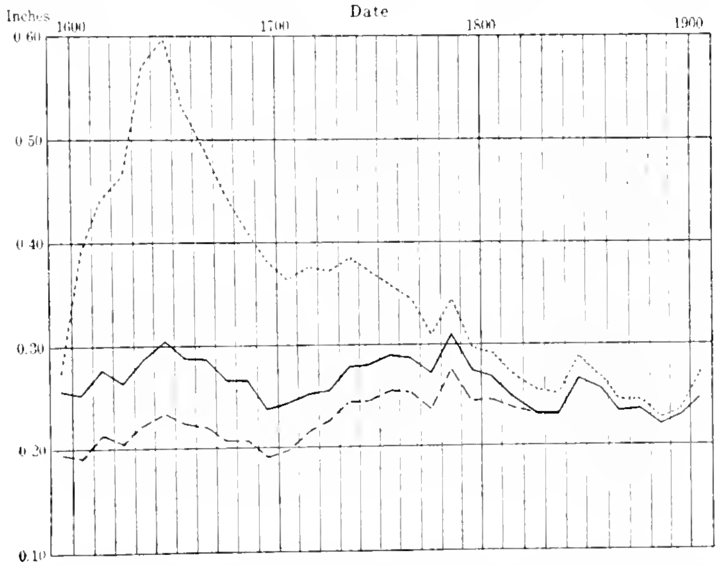


FIG. 29.—Curve of Growth of 50 Yellow Pines over 280 Years of Age, from 1590 to 1910 A. D.

The use of the corrective factor is illustrated in figure 29. In this case 50 of the oldest of the yellow pines of New Mexico have been taken, trees that began growing previous to 1630. The upper dotted line shows their rate of growth as actually measured; that is, before any correction has been applied. In its early portions for 50 years the curve rises with extreme rapidity; then for another 60 years it drops off almost equally fast; then we have another rise for 30 years, followed by a fall for 40, a rise for 20, and so on to the end. The irregularities are in part an indication of fluctuations of growth because of climatic variations or other accidents, but the main fall is due to the fact that after 1655 A. D. all the trees were of such age that their rate of growth was decreasing in accordance with the curve of figure 28. When the corrective factor for age is applied, the form of the curve is changed greatly and brought down to the position of the lower dash line. Here we find that the sinuosities continue to appear at the same periods as formerly, but their relative size is changed and those in the first century become more manifest because not masked by the extremely rapid growth of youth.

The curve as thus corrected for age drops extremely low in its early portions. If no further correction were necessary, we should infer that climatic conditions were very unfavorable during the seventeenth century. The low position, however, is due to the fact that no corrective factor for longevity has yet been applied.

The necessity for a correction for longevity is illustrated in figure 30, which represents an actual case of the same kind as that which appears in figure 27 in its simplest ideal form. The horizontal distances indicate various groups of trees, varying from those which were only 100 years of age at the time of cutting to a small group of three whose average age when cut was 390 years. The age of the trees of the respective groups is given in the upper row of figures just under the letters *A*, *B*, etc. The number of trees in each group is indicated in the second row of figures, and is also shown graphically in the rectangular diagram at the bottom of the figure. The groups of trees from Q to U have been included for the sake of completeness, but they may be disregarded not only because the number of trees in the last three groups is small, but because all the trees in these five groups are somewhat abnormal specimens, selected for cutting because of the fact that they had grown to large size in spite of their youth. With the older groups of trees this type of selection has had little influence, and beyond the age of 200 years we may safely pay no attention to it. Each of the sinuous lines in figure 30 is comparable, as has been said, to the single straight line of figure 27. It represents the average growth of each of the various groups during a particular decade. The successive lines represent the growth during successive decades up to the tenth, as indicated by the large figures on the right-hand side. Then there is a skip to the fifteenth and another to the twentieth decade. The small figures in parentheses at either end of each line indicate the dates for the particular decade and group there represented. The other small figures show how great a growth in inches was made during the respective decades by the terminal groups of each curve, that is, by group A^1 as shown on the right of each of the 12 curves, and by group U for the first ten decades, Q for the fifteenth, and L for the twentieth, as shown on the left. In each of the curves the actual figures derived from measurements are indicated by the fine line, while the heavy line represents the results obtained by smoothing according to the formula $\frac{a+b+c}{3}$. The process of smoothing is the simple one of taking the average of three successive points of the curve and plotting it for the middle point.

TABLE 3A.

1. Decade of age of trees.	2. Average growth in inches.	3. Smoothed average growth in inches.	4. Corrective factor for age.
1	0.46	0.46	0.50
2	0.58	0.58	0.39
3	0.63	0.63	0.37
4	0.61	0.61	0.38
5	0.57	0.57	0.40
6	0.545	0.54	0.43
7	0.495	0.51	0.45
8	0.465	0.48	0.48
9	0.445	0.45	0.51
10	0.44	0.43	0.53
11	0.415	0.41	0.56
12	0.41	0.39	0.59
13	0.385	0.37	0.62
14	0.37	0.35	0.66
15	0.335	0.335	0.69
16	0.33	0.32	0.72
17	0.325	0.305	0.75
18	0.305	0.29	0.79
19	0.275	0.28	0.82
20	0.27	0.27	0.85
21	0.28	0.26	0.88
22	0.265	0.255	0.90
23	0.21	0.25	0.92
24	0.26	0.245	0.94
25	0.25	0.245	0.95
26	0.26	0.24	0.96
27	0.265	0.24	0.96
28	0.245	0.24	0.97
29	0.25	0.235	0.98
30	0.22	0.235	0.98
31	0.225	0.23	0.99
32	0.23	0.23	1.00
33		0.23	1.00

From an examination of figure 30 it appears that the oldest group of trees (A^1) began to grow about 1520, and grew on an average only 0.15 inch during the first decade. The next group (A^2), which began life about 70 years later, grew about 0.29 inch during the first decade; the third group, 10 years younger, grew 0.41 inch; the fourth group (B) 0.45, etc., until we come to the youngest group (U) which grew 1.03 inches. Down to the tenth decade all the curves have a distinct slope from left to right, indicating that up to the age of 100 years the trees which are now old grew more slowly than those which have not yet attained great age, and most of which are not destined to attain such age. By the time the fifteenth decade is reached the difference between the rate of growth of old trees and younger trees has decreased notably, and in the twentieth decade it has disappeared. On the whole there is a steady decrease in the contrast between old trees and young from the first decade to the fifteenth or later. The object of the correction for longevity, here as everywhere, is to reduce curves like those now under discussion to straight, horizontal lines. If the oldest trees be taken as the standard, the greatest correction will be applied to trees of group U, that is, young trees during their first decade, and the correction will diminish to zero with the oldest group, A^1; it will also diminish as the trees increase in age until it becomes zero at the age of nearly 200 years. In practise I have found it advisable to treat the curves as straight, sloping lines and to assume that the divergence of each curve from a straight line is due merely to accidents and to the fact that the number of trees is not sufficient to eliminate accidental effects.

Returning now to figure 29, let us take the corrective factor for longevity as determined by the process just outlined and apply it to the curve already obtained by the application of the other corrective factor, that is, the factor for age. By so doing we raise the early parts of the curve, but leave the later parts untouched. This gives the final curve indicated in the solid line. In this the sinuosities still occur at the same places as in the original upper curve, but are more distinct than there. Taken as a whole the finally corrected curve does not trend markedly either up or down, though the portion included in the seventeenth century is on the whole somewhat higher than that of the two later centuries.

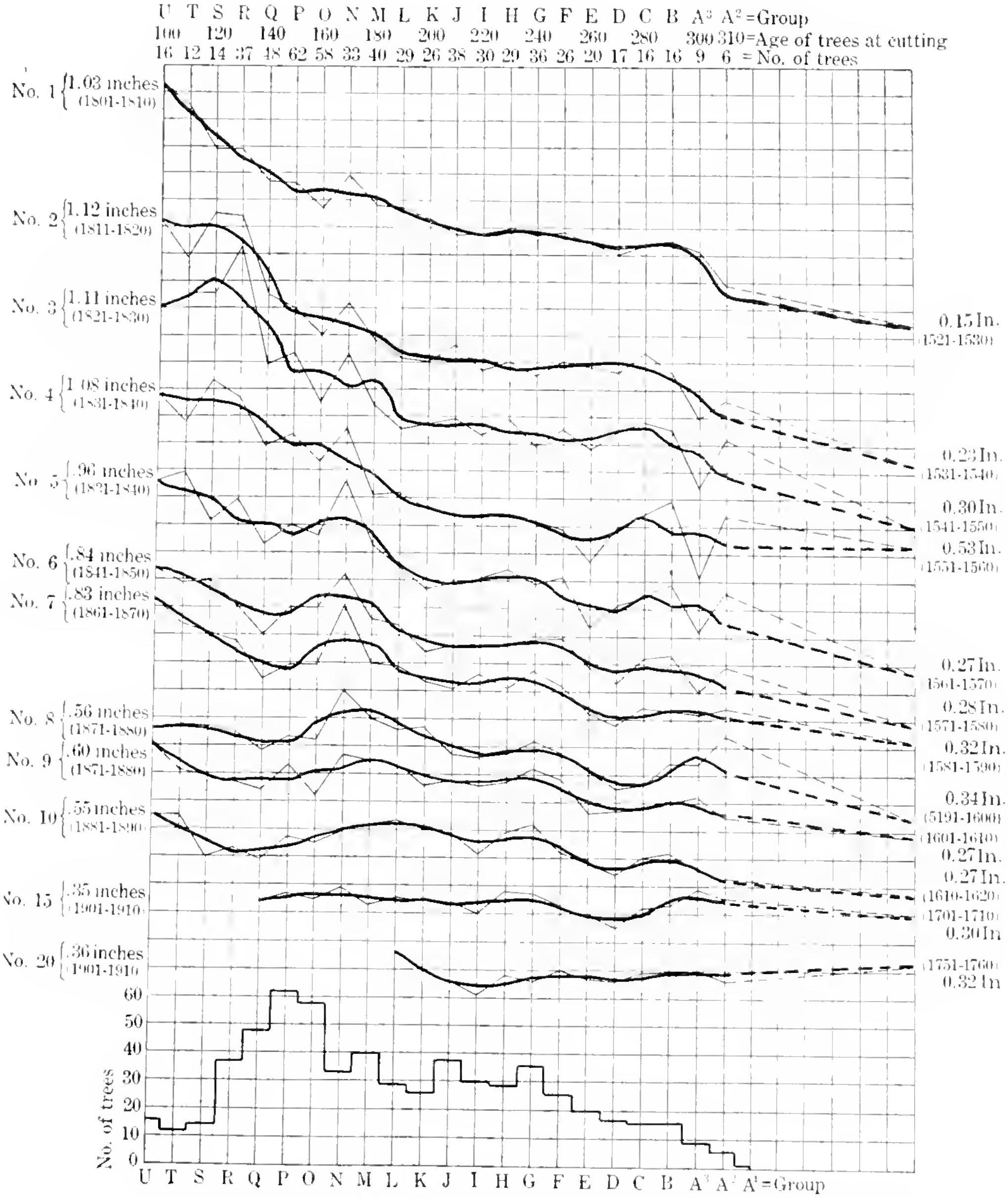


FIG. 30.—Variation in Radial Growth by Decades, Illustrating the Correction for Longevity of the Yellow Pine in New Mexico.

Vertical scale: one small square equals 0.20 inch.

Let us next examine the other curves derived from data furnished by the United States Forest Service. With these I have included the last 300 years of the curve of the *Sequoia washingtoniana* based on nearly 200 trees measured in 1911. This may here be treated in the same way as the others, although in the next chapter we shall consider the entire curve, going back 3,000 years and based on 450 trees, and shall discuss it in detail. The total number of curves available for 300 years, more or less, is 17, which are distributed from Maine to California. They are shown in figure 31. In most cases there is only one curve for a species, although the yellow pine, red fir, white oak, and spruce have two curves each, but from distinctly different localities. An attempt has been made to correct all the curves by the same method employed in the case of the yellow pine. In certain cases, however, the number of specimens is too small to allow of accuracy in the determination of the correction for longevity, and hence it has been omitted. In other cases, no correction for longevity appears to be required. Among the trees which do not require this correction only one, the short-leaved pine of Arkansas, is a conifer. The others—namely, the beech of New York, the white oak of Missouri, the white oak of West Virginia, and the tulip poplar of West Virginia—are deciduous. The number of trees varies from 26 in the case of the white oak of Missouri and 29 in the case of the Douglas fir of Idaho to 728 in the case of the white oak from West Virginia, Kentucky, and Tennessee. The figures for each tree are given in the diagrams and in Table H, pages 325–327.

The full significance of these curves can not yet be determined, but they are published here for the benefit of future investigators and because they enable us to arrive at greater certainty in some of our conclusions. The various groups are arranged partly according to place, but chiefly according to similarity, the curves at one extreme being quite diverse from those at the other. In general no curve is wholly different from those placed immediately beside it, but the first and second groups, although quite dissimilar, have been placed beside one another for the sake of contrast. All are characterized by pronounced fluctuations, having a periodicity of 100 to 200 years or more. In each group (excepting the last curve, that of the beech) the general form of the major fluctuations is similar, although details differ widely. I shall at present make no attempt to interpret the curves as a whole, for that is impossible in view of the absence of any exact, specific measurements of the growth year by year, such as Professor Douglass has obtained for the yellow pine, and such as I shall shortly present for the sequoia. Until these are obtained it would be rash to use the curves as the basis of an attempt to reconstruct the climate of the United States during the past 200 or 300 years; for different species of trees or the same species in different habitats may be stimulated by very different combinations of temperature and moisture, and a given species may find itself equally stimulated by two diverse combinations of these two factors. For example, to quote certain facts for which I am indebted to Mr. Raphael Zon, chief of silvics in the United States Forest Service, in regions like Idaho having two seasons of precipitation, winter and summer, the dry spring is the critical period. Therefore the fall of snow late in the winter is especially beneficial. In regions like California, having no rain whatever in summer, the same is true except that the entire amount of snowfall for the whole winter assumes a greater importance. In regions having precipitation at all seasons, on the other hand, the amount of winter snow makes little difference, provided the rains of summer, and especially spring, are abundant. But all trees are not equally stimulated by such rains, for some, such as the white oak and tulip poplar, require warmth as well as moisture, while others, like the beech, seem to demand only moisture and care little whether the temperature is above or below normal.

Before attempting to draw any conclusions from the curves, let us return to the question of how far their sinuosities are due to climatic variations, even though for most species the nature of those variations can not yet be determined. We have already spoken of the extent to which accidents, such as fires, the shading of trees during youth, the ravages of insects, and the change of conditions brought about by the white man's occupation of the country, may have influenced the shape of the curves. Now that we have them before us in their final corrected form, it will be profitable to consider these matters once more. Unquestionably, extensive forest fires not only kill trees by the thousand, but markedly diminish the rate of growth of those that remain living. Nevertheless, our 17 curves appear to have been little influenced in this way. In the first place, previous to the coming of Europeans and to the introduction of locomotives, fires were probably not one-tenth as numerous as now; they were due either to lightning or to the carelessness of the Indians.

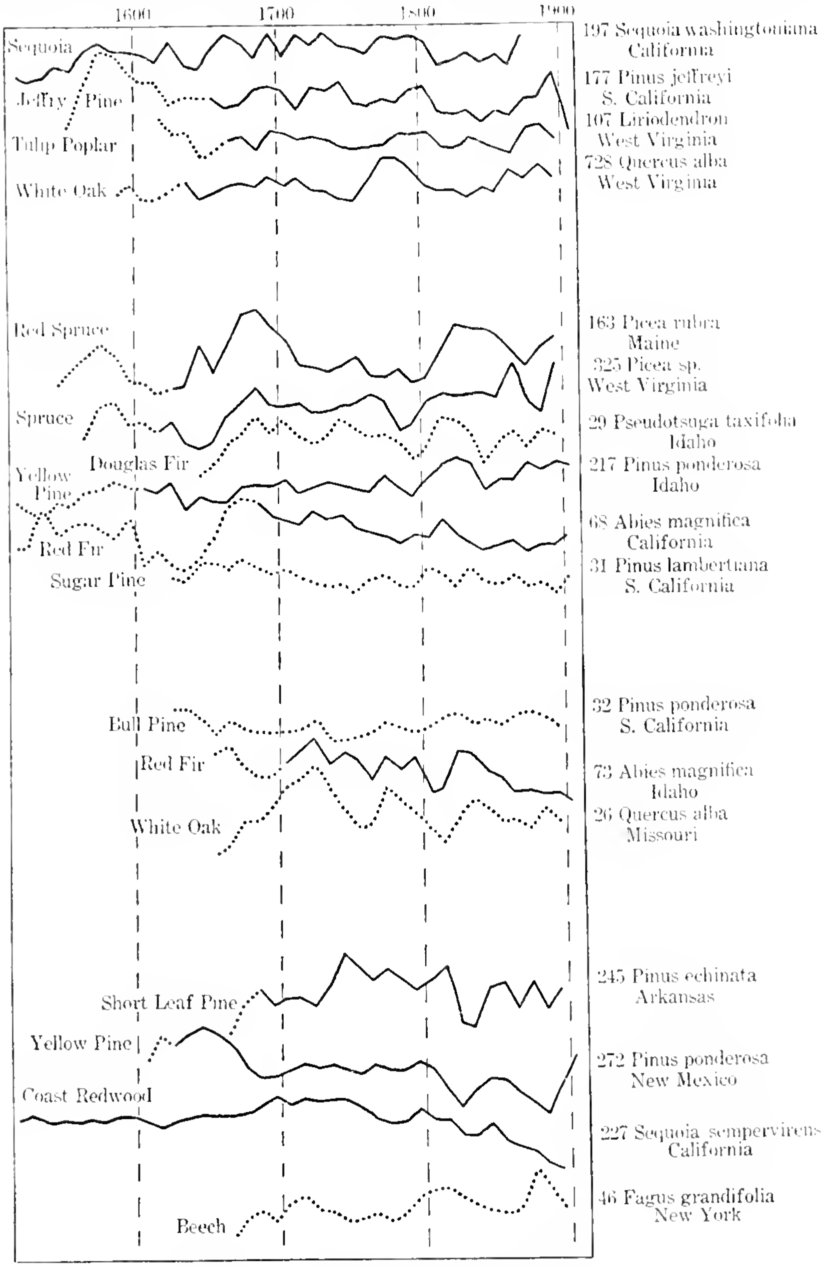


Fig. 31.—Curves of Growth of American Trees.
(See Table II, pp. 325–327.)

The Indians, however, were few in number, and, according to all accounts, generally took great care to extinguish their fires or to kindle them in places where they could not spread. Still, even in their day, there must have been a certain number of fires, and traces of these can sometimes be seen in charred spots far toward the center of a great tree. These fires must have produced effects which are apparent in some of our curves. On the whole, as we have already seen, fires would occur during dry seasons, and hence any diminution of growth due to them would simply accentuate the diminution due to the drought. In spite of this, however, most of the sinuosities in the curves are apparently not due to fires. The reason for this conclusion is twofold.

In the first place, practically every one of our curves is based upon trees which did not grow in one restricted locality, but were spread over a wide area. For instance, the yellow pines of New Mexico came from forests all over the State; the white oaks came from four or five localities in the States of Tennessee, West Virginia, and Kentucky; and the giant redwoods were from four localities in the Sierra Nevadas from 5 to 60 miles apart. It is far from probable that a single fire would affect all these trees at once, and in most cases the number of trees from a given locality is not sufficient to produce more than a slight effect upon the general curve unless the fire were very widespread.

The second reason for believing that fires have had no great effect in producing the sinuosities of the curves is stronger. A fire causes an immediate decrease in the tree's rate of growth. It is followed by years of gradual recovery. Therefore in the case of a fire the curve ought to drop suddenly and then rise gradually. Sometimes this occurs, but in most cases the drop in the curves is not confined to a single decade but continues through periods of from 20 to 50 years. In a large number of cases, also, the rise in the curve is more sudden than the succeeding or preceding fall, indicating that the growth of the trees received a somewhat sudden impulse, which was followed by a long period of gradual decline. Manifestly this is exactly the opposite of what would occur in the case of a fire.

Another important cause of differences in the rate of growth of trees is the amount of sunlight or shade to which they are subjected. With young trees this is undoubtedly a matter of extreme importance, and if our curves were based wholly on immature trees it would render them almost valueless. As a matter of fact, however, the curves are based on the largest trees, those which for centuries have been dominant. In practically all cases the first 10 years of the life of the trees are not used in our curves, and in many cases a larger number of years is omitted. Nevertheless in their youth the trees which we have employed were doubtless shaded by other trees. Through the greater part of their lives, however, they towered to full height and were not overcrowded. Moreover, even if shading did prevent normal growth in a young tree, after the trees which overshadowed such an individual had died, other trees could scarcely grow up so fast as to overshadow it again. In other words, the shading of one tree by another might make the curve of growth very low in youth and high in old age, but it could not cause it to fluctuate back and forth from high to low. Therefore we must conclude that while shading is an important factor in youth and may largely influence the beginnings of the curve of growth of each tree it is not an important factor after maturity is reached.

It is not easy to estimate the ravages of insects. Doubtless they, too, like fires or shading, often check the growth of the forests. The same arguments, however, apply to them as to fires. Their ravages are apt to be local and would not be likely to influence trees so widely scattered as those which we have used. Moreover, when trees are attacked seriously by insects or other parasites the chances are that the trees so affected will die, but the trees which have been used in our curves are for the most part uncommonly large and elderly individuals which show little sign of disease.

As to the effect of man, little need be said. Most of our curves are derived from regions where man's influence has not been felt until within a few years. Even in long-settled regions the sinuosities of the part of each curve belonging to a period two or three centuries ago do not indicate that conditions were then essentially different from those which now prevail after the coming of the white man.

In discussing the reasons for thinking that the sinuosities in the curves are not of accidental origin, we have been dealing with the matter negatively. There are, however, distinct positive reasons for thinking that they are due to climatic pulsations. The first of these has already been given, namely, the agreement which Professor Douglass finds between annual variations in the rate of growth of the yellow pine and in the rainfall. Subsequent to the publication of his original paper other investigators have come to the same conclusion in respect to other trees; and in the next chapter I shall show how far it is true in respect to the *Sequoia washingtoniana* of California. Another strong reason for the belief that climatic pulsations are the cause of the fluctuations in the curve is found in the agreement of curves for widely different areas; for instance, the curves derived from 32 specimens of the bull pine of San Bernardino County, in southern California, from 73 specimens of the red fir at Henry's Lake, Idaho, and from 26 specimens of the white oak in Fenton, Missouri, all agree in having a marked maximum between 1720 and 1730 A. D., a minor maximum between 1770 and 1780, and a second marked maximum between 1820 and 1830—or, in the case of the white oak, a decade later. In other cases there is a similar agreement: for example, the 163 specimens of red spruce from Piscataqua County, Maine, the 223 spruces from Nicholas County, West Virginia, and the 29 Douglas firs from the Salmon Forest, Idaho, all have a pronounced maximum between 1680 and 1690 A. D. Next comes a period of slow growth, lasting a century or more, but broken by a slight maximum about half-way. Then again the curves rise, and reach a maximum between 1810 and 1830. On the other hand, the white oak of West Virginia, with its 728 trees, has its maxima and minima at almost opposite times from those of the red spruce from Maine. In the same way the curves of the bull pine of southern California and the *Sequoia sempervirens* from the northern part of the State are almost diametrically opposed to one another. This is not surprising, for the records of the 30 years from 1878 to 1908 show that the main fluctuations of the rainfall of these two regions are in general the reverse of one another, which is precisely what we should infer from the trees.

The evidence of these 17 curves of growth, so far as our main problem of climatic changes is concerned, all points to one conclusion. The growth of trees in the United States seems to be characterized by long and important cycles, having a periodicity of 100 or 200 years, more or less, and affecting all parts of the country. So widespread a phenomenon can scarcely be due to anything but climate. If we were able to interpret each curve more exactly in terms of rainfall, snowfall, drought, temperature and the like, we should probably find the agreement much closer than is now the case. The very fact, however, that curves from Maine and Idaho, or from southern California and Missouri, agree so closely, seems to prove that climatic pulsations of relatively long period affect the whole country almost simultaneously, and can be read in the trees. It must not be inferred, however, that the effect is supposed to be the same in all places. A change which causes drought in the north may produce an excess of moisture in the south.

The possibility of this is well illustrated in figure 32, which shows two curves for the

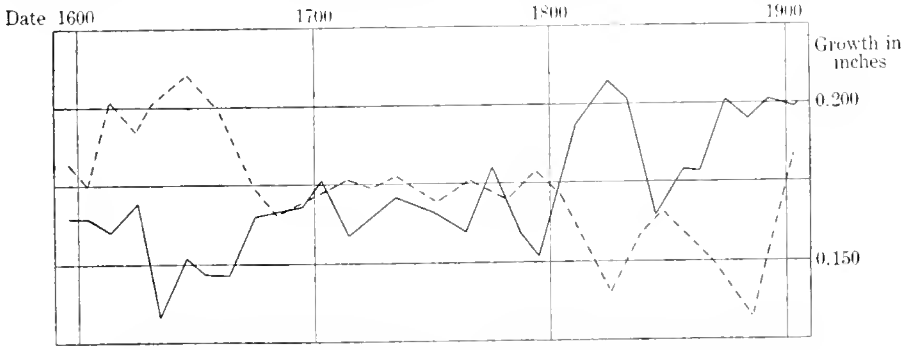


Fig. 32.—Curves of Growth of Western Yellow Pine in New Mexico (dotted line) and Idaho (solid line). (See Table H, pp. 325–327.)

yellow pine, one in New Mexico (the dotted line which we have already considered) and the other the curve for 217 trees in Idaho. The two curves were prepared in exactly the same way, and to both the corrections for age and longevity were applied according to the same mathematical processes. Nevertheless, they are almost diametrically opposed. Where one rises to a maximum the other is depressed to a minimum, and the opposition is evident in practically every case. Between 1600 and 1700 it is especially noticeable. During the next century, when climatic conditions were less extreme, the difference in the curves becomes less marked, and they run along together in a medial position. Then, in the nineteenth century, when drought was severe in New Mexico, the two curves are again in marked opposition. Moreover, the general trend of the New Mexican curve is downward, indicating that, on the whole, conditions during the past three centuries have become less favorable to the growth of the yellow pine in that region. The Idaho curve, on the contrary, tends upward, suggesting that conditions have there become more and more favorable. Much stress must not be laid on this last point, however, for the opposed trends may be due partly to errors in the determination of the corrective factors.

The relation between the two curves of the yellow pine is susceptible of two interpretations. In the first place, it may indicate that rainy periods in New Mexico are synchronous with dry periods in Idaho; or, in the second place, it may mean that droughts are synchronous in the two regions, but that the trees of New Mexico, growing in a warmer, drier region than the others, are stimulated by long winters, heavy snowfall, and late, moist springs, while those of Idaho are hindered by the same conditions. An examination of the rainfall of the two regions seems to confirm the first possibility. For purposes of comparison I have taken all the stations in Idaho, five in number, and in western and central New Mexico, including El Paso on the border of Texas, seven in number, which have continuous rainfall records since 1894. The Idaho stations range from 1,665 to 4,191 feet in altitude, with an average altitude of 2,700 feet. Their mean annual temperature ranges from 43.4° F. to 51.3° F., with an average of 46.9° F. The New Mexican stations vary in altitude from 3,760 to 7,000 feet with an average of 5,150 feet, while their mean annual temperature ranges from 49.2° F. to 63.7° F. and averages 56.5°. In both cases the meteorological stations are 2,000 to 3,000 feet lower than the region where the pines

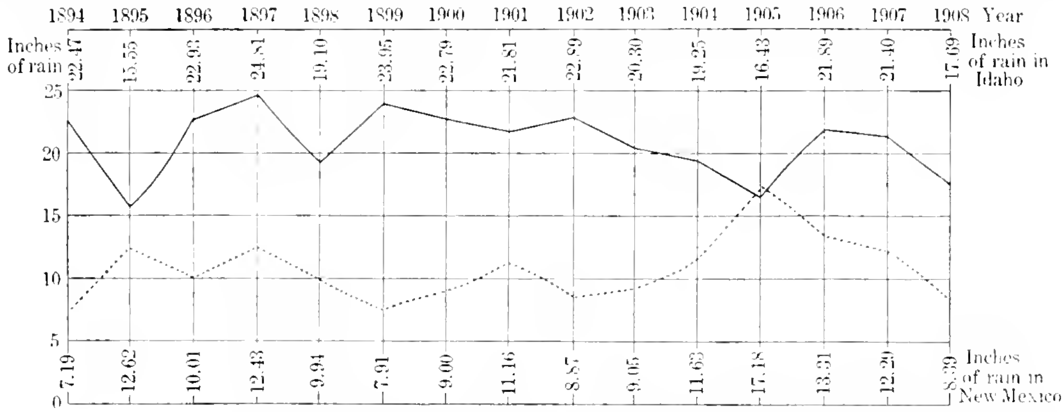


FIG. 33.—Rainfall of Idaho (solid line) Compared with that of New Mexico (dotted line).

grow, but the relative conditions are approximately the same. The trees of Idaho certainly grow where the climate is cooler and more rainy than in the parts of New Mexico where their species flourishes. Nevertheless, in both cases moisture seems to be the factor of chief importance. Figure 33 illustrates the matter; it shows the average rainfall of the five Idaho stations year by year compared with the seven New Mexican stations. In only 4 cases out of 14 does the line connecting one year with the next slope the same way in both curves. In other words, when the rainfall of Idaho increases that of New Mexico decreases, and the reverse, which is exactly the same thing that takes place in the growth of the trees. The way in which the two sets of curves representing climate and growth agree in presenting opposite phases in the two areas goes far toward proving that the method of Professor Douglass can be relied upon.

Before leaving this subject I would call attention to the fact that while the precipitation of New Mexico is predominantly of the monsoon, summer, or continental type, and that of Idaho is of the more northerly type, dependent on cyclonic storms and falling chiefly in winter, both are distinctly of a mixed type. The opposition of the two curves harmonizes with the opposition of the summer and winter rains at Tucson as described in Chapter I. In Chapter XVI, on the shifting of climatic zones, we come to the conclusion that changes of climate are probably characterized by an alternate strengthening and weakening of the earth's winds by reason of an increase or decrease in the intensity of barometric pressure. Such a strengthening of the winds would at first thought seem to cause an increase or decrease of both summer and winter rainfall at the same period. This, however, does not seem to be the case in the minor variations now under consideration, although it appears to be true when we come to the larger variations discussed in Chapter XVI, where the shifting of climatic zones is considered. Possibly this discrepancy is due to the movement of Arctowski's "pleions" and "antipleions," or areas of excess or deficiency of temperature, rainfall, and so forth. These, as will be shown more fully in Chapter XIX, move back and forth in short periods. They are located chiefly within the limits of the United States and seem to be a purely continental phenomenon. Another possibility is that Idaho lies so far north that the shifting of zones, which is discussed hereafter, brings it into what is now the far northern region of light rainfall at a time when New Mexico comes into an area of heavy rainfall. As yet the matter is so little understood that any satisfactory explanation is impossible.

As a final method of testing the value of the curves discussed in this chapter, let us see how the curve for New Mexico agrees with the conclusions which we have already reached on the basis of the evidence of terraces, archeology, and history. In this connection I would emphasize the fact that these conclusions were all reached before the trees had been investigated. They have been set down in previous chapters exactly as they were reached at a period of from 5 to 15 months before the tree measurements were investigated. The importance of this lies in the fact that the agreement of the mathematically derived tree curves with the conclusions derived from entirely different methods furnishes strong confirmation of the accuracy of those methods as employed not only in America but in Asia and southern Europe.

From the ruins of Gran Quivira, it will be remembered, we concluded that at the time of the Spanish occupation of New Mexico in the first half of the seventeenth century climatic conditions were distinctly more favorable than at present. About 1672 the ruins of Gran Quivira seem to have been finally abandoned at the time of the Pueblo rebellion. During the succeeding century conditions appear to have been somewhat better than during the one that ended in 1900, as appears probable from the ruins of Buzani and one or two other places not here mentioned. Let us compare the course of events thus indicated with the final curve of growth of the yellow pines of New Mexico as derived from 272 trees and as shown in the dotted line of figure 32. The high parts of the curve, according to the conclusive investigations of Professor Douglass, point to moist conditions, and the low to dry. If we interpret the curve in this way, it appears that perhaps one reason why the Spaniards were able to establish themselves in New Mexico almost without a blow was that from 1600 to 1650 the amount of rain and the general conditions of the growth of vegetation were not only more favorable than now, but were becoming better from year to year. Places like Gran Quivira were readily habitable and were growingly prosperous, so far as their prosperity depended upon good crops. Under such circumstances the ignorant Pueblo Indians would naturally look upon the coming of the Spaniards as a blessing. A decrease in rainfall begins to be apparent between 1650 and 1660, but it is unimportant at first, as we infer from the fact that the growth of the trees (and impliedly of the crops) continues to be well above the normal until about 1665. Thereafter a rapid deterioration takes place, which culminates about 1680 or soon after. During that period a widespread uprising took place against the Spaniards, the Pueblo rebellion which ousted the Europeans for some years. Doubtless its immediate cause was the arrogance and cruelty of some of the Spaniards, but back of that there probably lay a deep-seated discontent. Want and famine must have prevailed, and if the Indians were like the rest of mankind they doubtless ascribed their misfortunes to their conquerors.

The further elucidation of the causes of the Pueblo rebellion is an historical matter which can not be discussed at this time. It is worth while, however, to mention a single piece of corroborative evidence. Mr. E. E. Free has called my attention to an account of an old census given by Mr. J. W. Curd in the El Paso *Times*. In this document there appears an interesting reference to bad crops. El Paso, although in Texas, lies almost at the middle of the southern boundary of New Mexico. The document is a census of that town dated September 11, 1684, and contains a list of 109 Spanish families living near El Paso. It is signed by the Spanish governor. To quote Mr. Curd:

"While the document is nothing more than a dry and uninteresting census roll, it is illuminative of the terrible devastation and suffering that resulted from the Indian revolt in 1680. This revolt destroyed some 42 presidios and missions in New Mexico north of El Paso, and the remnant of Spaniards and friendly Indians took refuge in Guadalupe del Passo (El Paso). While the Mission Guadalupe was a rich one and additional supplies were forwarded from Mexico City the people still suffered much from lack of clothing and food. The census shows that what crops were planted that year consisted only of maize, which, owing to drought, was an almost total failure. What maize was grown was eaten green, so that there was no supply for winter."

The full investigation of this famine and its effects must be left to the historians. The coincidence, however, between the curve of the trees, an extraordinary drought and famine, the last and worst stages of the Pueblo rebellion, and the final abandonment of places like Gran Quivira can not be passed unnoticed. After 1680 conditions appear to have improved; the eighteenth century, although a period of less rainfall than during the time of the early Spanish occupation, was more propitious than the century which has just closed.

A

B

A. The Boule tree, a Sequoia probably 2,500 years old. The size may be judged from the man and ladder in the cavity at the base.
B. Young and middle-aged Sequoias in a valley bottom. This shows how rapidly the trees reproduce themselves where moisture is abundant. On the hillsides, such as those of A, there is practically no reproduction.

CHAPTER XIII.

THE CURVE OF THE BIG TREES.

The curves of tree growth thus far examined all belong to relatively recent times. Yet their length of 200 to 300 years suffices to indicate the existence of climatic cycles longer than any which are deducible from actual meteorological records; hence we are led to expect that longer curves would indicate still longer cycles. The tree which gives most promise of furnishing a long curve is obviously the *Sequoia washingtoniana** of California. This tree is not only the largest species existing at present, but also the longest-lived, so far as we have certain knowledge. A few other species, such as the baobab, are known to live to great age, but as they are denizens of tropical countries where seasonal variations are slight, they do not produce marked annual rings which can easily and accurately be measured. The cedar of Lebanon is another old tree. A branch of this which broke off a few years ago is said to have been 2,000 years old, according to a count of the rings made by an American member of the faculty of the Syrian Protestant College at Beirut. Unfortunately, however, the number of really old cedars is limited to a few score, and it is to be hoped that these will be available for measurement for many years to come. In India, among the Hima ayas, certain species of great age and size may eventually give valuable records, but they are not likely to carry us back half as far as does the *Sequoia washingtoniana*. The same is true in Australia, although it, also, has some old trees of great size. Thus there is reason to think that the sequoia will always be the most important tree in this respect, not only because of its extraordinary age and size, but because a large number of the trees are readily accessible and are being cut year by year, a few at a time, in a way to render them easily available for study. It may seem a pity that trees thousands of years of age should be cut for fence posts and "shakes," but it is fortunate for our present investigation. Nor is it a matter of much regret from the point of view of future generations, for the United States Forest Service has wisely reserved most of the areas where the trees abound, and only the most conservative cutting will there be permitted. Moreover, the areas which are owned privately, and of which the Government can not afford to take possession, revert to the public domain as soon as the lumber is cut, so that as new trees grow they will be preserved for the future.

A curve of growth such as that of the *Sequoia washingtoniana* is important not merely or chiefly as a record of local climatic conditions, but as a standard from which may be deduced the climate of any part of the world during the past 2,000 or 3,000 years. According to the growing consensus of opinion among meteorologists, the more marked climatic variations of different parts of the world are intimately coördinated; and this conclusion, as we have seen, is confirmed by the studies of the present volume. As yet the relation between various factors in different parts of the world, such as rainfall in tropical Africa and winds in the Sahara, or storms in central Asia and the monsoons in India, has not been determined with precision, but this is gradually being accomplished. The great difficulty lies in the fact that exact meteorological records are nowhere available for a period of much over a century, and in most places for less than half that time. They

* The California Big Tree has often been known as *Sequoia gigantea* Endl. That name, however, is synonymous with *Sequoia sempervirens*, the redwood. The earliest name applied to the Big Tree is *Taxodium washingtonianum* Winslow, published in 1854. The combination *Sequoia washingtoniana* was made by Sudworth in 1898, and this is the name that must stand for the species. Jepson, in his Silva of California, uses for this tree the name *Sequoia gigantea* Decaisne, dating from 1854, but since this is obviously a homonym of Endlicher's name, it is untenable.

do not cover the whole of a single one of the longer cycles. Yet long records are essential if we would understand what has really happened in the past and thus put ourselves in a position to determine the cause of present changes and to arrive at the ability to predict those of the future. Such a knowledge is equally essential if we would understand all the varied and important effects which climatic pulsations, working through famine, migration, and other causes, have produced upon man in the past and are likely to produce upon him in the future. Only by such knowledge of the past, apparently, and by the ability to predict the future, can we be sure to avoid calamities akin to some which have overwhelmed certain portions of the earth at various historic periods. Seemingly, then, it is not only of scientific interest, but of direct practical value, to be able to extend our climatic records as far back as possible in all parts of the world.

If the method of interpreting the growth of trees introduced by Douglass and amplified in this volume commends itself to the scientific world and is widely adopted, the work of a decade or two, or at most of a generation, ought to give us curves of tree growth extending back 300 years more or less in all the chief parts of the earth. A comparison of the later portion of each curve with the local meteorological records for a few decades will show what kind of weather conditions promote or retard growth and will enable us to determine the kind of cells and the proportion of different kinds which grow in years of particular types. If the curves of several species are available from the same area, and if the cellular structure is carefully studied in each case, it will not only be possible to interpret each curve from beginning to end, but it will also probably be feasible to draw curves representing changes in special types of meteorological phenomena, such as the amount of rain, its distribution, the length and temperature of the growing season, and the other factors which are of chief importance in determining the rate of growth of vegetation. The curves thus obtained, being derived from a great number of trees of several species scattered over a considerable area, will represent average conditions in a way that is possible only with a large number of meteorological stations. More important than this is the fact that the tree curves sum up the effect of all sorts of meteorological conditions upon vegetation. This effect is of paramount importance, as is clear from the fact that the primary object of the greatest weather bureaus is to furnish statistics and predictions of weather for the benefit of agriculture. Various attempts have been made to combine precipitation, temperature, length of seasons, evaporation, the monthly distribution of rainfall, and other factors into a single curve which should sum up the effect of the weather upon plant life, but the results have not been satisfactory. Tree curves, however, seem to furnish exactly what is wanted. Of course large numbers of them are necessary, but the expense of obtaining them is not 1 per cent as great as the expense of obtaining reliable meteorological records year after year.

When we have obtained reliable climatic curves for various parts of the world covering a period of two or three centuries, we shall probably be in a position to make most instructive comparisons of one country with another. If meteorologists are right in thinking that no great change in the circulation of the atmosphere, or in any of the other climatic elements, can take place in one part of the world without a corresponding change of some sort in other parts, it ought ultimately to be possible to say that a change of a certain sort in California is indicative of such and such a change of quite a different kind in China, South Africa, or some other part of the world. By this I do not mean that minor changes, such as those of a single year, can be correlated in different regions, but only the main ones, those that belong to long cycles (such as Brückner's 35-year cycle) or, still more, to the much greater cycles of which the studies of this volume seem to furnish evidence. Granting, then, that a pronounced change can not take place in one part of the earth's atmosphere without inducing some sort of variation in other parts, it seems to follow that from a single long curve like that of California we can work out the main changes in all parts of the world. Other lines of evidence will furnish assistance, and little by little the curves of other trees will be carried back farther and farther; yet for the present, and probably for a long time to come, the curve of the *Sequoia washingtoniana* is likely to be the most important of all lines of evidence as to the climate of the last 2,000 to 3,000 years. We may add that it is likely to be one of the most important lines of evidence as to the climate of the future, for it will probably give us more knowledge of prolonged cycles and more data for use in the determination of the causes of climatic changes than will any other individual group of facts. Hence it behooves us to treat the subject with the utmost care and to use every possible means of obtaining high accuracy.

The *Sequoia washingtoniana,* as is well known, is one of two species of redwood, a genus which grows in California, and nowhere else. The other species is the *Sequoia sempervirens,* or coast redwood, which possesses many of the qualities of its cousin, the giant redwood, but attains neither such great age nor such great size. It flourishes in the Coast Range of California, from a point about 100 miles south of San Francisco to the northern part of the State. It is never found at any great distance from the sea, for its habitat is limited to places on the western slope of the mountains, where summer fogs keep the air moist and where the precipitation is heavy because the winds from the west are there first compelled to rise. The other redwood, the giant species with which we are mainly concerned, grows in a similar environment among the Sierra Nevadas. Its habitat is limited to a narrow strip 250 miles long, beginning near latitude 36°, in the mountains east of Portersville, and extending northwest as far as latitude 39°, west of Lake Tahoe. The trees are found only near the western edge of the mountains, at an altitude which rarely falls below 5,000 feet even at the northern limits, and rarely rises above 7,000 even in the south. In any given locality the range is almost never more than 1,000 feet.

The giant sequoia is strictly limited to a narrow band of abundant precipitation. As the westerly winds come from the Pacific Ocean they first cross the coastal belt of cold water which prevails along much of the California shore. There they are so chilled, especially in summer, that their moisture is condensed into fogs. Then they rise over the Coast Range, and in so doing are once more cooled and obliged to give up moisture in the form of rain. These two sources of moisture make possible the existence of the *Sequoia sempervirens,* but only in its own special, narrow strip.

Proceeding eastward the winds descend into the inner valley of California, and by so doing become warm and capable of holding much moisture. Hence the valley is dry, especially on the west side, where the winds first descend. Farther eastward the air is once more forced to rise by the Sierras. At first it does not give up much moisture, because it has already lost so much in crossing the Coast Range. Only when it gets to an elevation higher than that reached in crossing those mountains does condensation begin to take place on a large scale. Thereafter precipitation increases rapidly for 2,000 to 3,000 feet, after which it begins to decrease. The decrease is due partly to the fact that after a certain point the actual amount of moisture which the cooled air is capable of holding becomes slight, and a large amount of cooling is necessary in order to cause its precipitation, and partly because after a height of 6,000 to 7,000 feet is attained the mountains no longer rise steeply, so that the cooling of the air is less rapid than on the front of the mountains. These various conditions give rise to a narrow belt of heavy rainfall with drier areas on either side, and in this belt alone the giant redwood flourishes. Along with it grow pines and cedars, which are able also to grow at both higher and lower altitudes than the sequoia. Another common tree is the white fir, which, with the Douglas fir, is found in abundance not only with the sequoia, but in places too high and cold for it. Bushes as well as great trees abound in the well-watered sequoia zone, and some, like the azalea, seem to be almost as particular about their location as are the Big Trees. The azaleas' white flowers, tinged with orange and pink, are often banked in great masses in the bottoms of the same moist valleys where the sequoia dwells.

Every one has heard of the vast size and great age of the Big Trees of California. The trunk of a well-grown specimen has a diameter of 25 to 30 feet, which is equal to the width of an ordinary house. Such a tree sometimes towers 300 feet, or 4 times as high as a large elm, and within 25 feet of the top the trunk is still 10 or 12 feet in thickness. Three thousand fence-posts, sufficient to support a wire fence around 8,000 to 9,000 acres, have been made from one of these giants, and that was only the first step toward using its huge carcass. The second item of its product consisted of 650,000 shingles, enough to cover the roofs of 70 to 80 houses. Finally, there still remained hundreds of cords of firewood which no one could use because of the prohibitive expense of hauling the wood out of the mountains. The upper third of the trunk and all the branches lie on the ground where they fell, not visibly rotting, for the wood is wonderfully enduring, but simply waiting until some foolish camper shall light a devastating fire.

Huge as the sequoias are, their size is scarcely so wonderful as their age. A tree that has lived 500 years is still in its early youth; one that has rounded out 1,000 summers and winters is only in full maturity; and old age, the threescore years and ten of the sequoias, does not come for 17 or 18 centuries. How old the oldest trees may be is not yet certain, but during our two seasons of field work in 1911 and 1912 we counted the rings of 79 that were over 2,000 years of age, of 3 that were over 3,000 years, and of 1 that was 3,210 years. In the days of the Trojan War and of the exodus of the Hebrews from Egypt, this oldest tree was a sturdy sapling, with stiff, prickly foliage like that of a cedar, but far more compressed. It was doubtless a graceful, sharply conical tree, 20 to 30 feet high, with dense, horizontal branches, the lower ones of which swept the ground. Like the young trees of to-day, the ancient sequoia and the clump of trees of similar age which grew close to it must have been a charming adornment of the landscape. By the time of Marathon the trees had lost the hard, sharp lines of youth and were thoroughly mature. The lower branches had disappeared, up to a height of 100 feet or more; the giant trunks were disclosed as bare, reddish columns covered with soft bark 6 to 12 inches in thickness; the upper branches had acquired a slightly drooping aspect; and the spiny foliage, far removed from the ground, had assumed a graceful, rounded appearance. Then for centuries, through the days of Rome, the Dark Ages, and all the period of the growth of European civilization, the ancient giants preserved the same appearance, strong and solid, but with a strangely attractive, approachable quality.

Before proceeding to more technical matters, a brief description of our method of work may not be amiss. Toward the end of May, 1911, I left the railroad at Sanger, near Fresno, in the great inner valley of California, and with two assistants drove up into the mountains through the General Grant National Park to Indian Basin, about 3 miles west of Hume, in a tract belonging to the Hume-Bennett Lumber Company. There we camped for two weeks, and then went to a similar region some 60 miles farther south on the Tulare River, east of Portersville, where we spent a slightly longer time. The next year, in early June, with Professor H. S. Canby, of Yale University, and five student assistants from California, I went again to the Hume region and spent a month camped at various points at distances of from 2 to 10 miles from Hume. After my departure my assistants remained another month in the Converse Basin. One of them, Mr. Hiram E. Miller, was with me in both 1911 and 1912, and in the latter year took charge of the work during the last month. His carefulness and efficiency make me feel as much confidence in the results obtained after I left as in those obtained under my own personal supervision.

The method employed by the lumbermen in cutting the trees furnishes a smooth sawed surface over half the area of the stump. Before the lumbermen attack one of the giants, they build a platform about it 6 feet or more above the ground and high enough to be clear of the most flaring portion of the trunk. On this two men stand and chop out huge chips sometimes 18 inches long. As the cutting proceeds, a great notch is formed, flat on the bottom and high enough so that the men actually stand within it. In this way they chop 10 feet more or less into the tree, until they approach the center. Then they take a band-saw, 20 feet or more in length, and go around to the other side. For the next few days they pull the great saw back and forth, soaking it liberally in grease to make it slip easily, and driving wedges behind it in order to prevent the weight of the tree from resting on the saw. Finally, when the tree is almost cut through, more wedging is done, and the helpless trunk topples over with a thud and a stupendous cracking of branches that can be heard a mile. The sawn surface exposes the rings of growth so that all one has to do is to measure them, provided the cutting has taken place recently.

Even in old stumps it is comparatively easy to measure the rings. The sequoia is so wonderfully durable that as soon as one cuts half an inch below the surface of a stump the wood is almost fresh, even though 30 years have elapsed since the tree was cut. This, however, is true only of the heart-wood. The 6 inches of wood on the outside of each trunk, that is, the portion in which sap was actually flowing at the time of cutting, are of quite a different quality. The wood is white instead of deep red like the main body of the trunk, it is soft, and it decays rapidly, so that at the end of 20 to 30 years it is often quite rotten, although enough generally remains to permit the counting of the rings. On the smoothly sawn surface of the stumps the rings are often so clear that one can measure them easily and accurately with no preparation whatever, or else with no preparation except scraping off the pitchy sap which has been exuded from within, or brushing off an accumulation of pine needles and dirt with a whisk broom. A little experience, however, soon taught us that while the larger rings could be measured with accuracy, the smaller ones were apt to be missed unless greater precautions were taken. Therefore we made it a practise to chisel grooves an inch or more deep in the more difficult portions of each tree, and in the latter half of our work we chiseled the entire distance except for some of the large rings toward the center. During the first season, except in the case of especially old or difficult specimens, only one measurement was made upon each tree. Our practise was to select the best possible radius, usually the longest and clearest, and always as free as possible from knots. During the second year we invariably measured two radii on each tree, and often three or even four. We also went back to many of the trees done the year before and measured them again along other radii.

One of our chief difficulties lay in the fact that in bad seasons one side of a tree often fails to lay on any wood, especially in cases where a clump of trees grow together in the sequoias' usual habit, and the inner portions do not have a fair chance. Often we found a difference of 20 to 30 years in radii at right angles to one another; and in one extreme case, one side of a tree 3,000 years old was 500 years older than the other, according to our count. All these things necessitated constant care in order that our results might be correct. Another trial lay in the fact that in spite of the extraordinary durability of the wood, a certain number of decayed places are found, especially at the centers of the older trees, exactly the portions which one most desires to see preserved.

The net result of our work is summed up in the tables on pages 301 to 330. From these it will be seen that we measured a total of 462 trees, 11 of which were entirely discarded, because repeated measurements failed to agree, or because of other known sources of error. Among the 451 trees actually used, 108 were measured along only one radius, 234 along two radii, 89 along three, 18 along four, and 2 along five. For the most part those measured along only one radius were young trees in which there was small opportunity for error. A number, however, were old trees located in the valley of the Tulare River which we visited in 1911, but did not return to in 1912. A few others, located in regions which we revisited, could not be found a second time, or else could not be identified because at the beginning of our work we failed to number the stumps, a practise which we followed carefully most of the time. The numbers were chiseled on the flat surface, and are there for future identification if other investigators carry this work farther. The total number of measurements, excluding trees not used, amounts to 925, which makes an average of over 2 for each tree. Some of these were discarded, leaving 785 as the number actually used.

As a rule three measurements were made only in cases where the first two differed by more than 1 per cent. More than three were made only upon trees of exceptional difficulty. The age of the trees at the time of cutting varied from 250 to 3,210 years. The average is approximately 1,400. Including the 28 measurements of the 11 discarded trees, the number of individual decades measured during our two seasons of work amounts to approximately 111,700, while the number of rings actually counted was ten times as great, or 1,117,000. So large a number of measurements ought to give results of fairly high accuracy. Inasmuch as the number of trees which go back 2,000 years is 79, considerable accuracy is possible at that remote time; and even at a date 600 years earlier, where 10 trees are available, the results are sufficiently accurate to indicate the main outlines of the climatic curve, although the vagaries of individual decades are not reliable and the general fluctuations are exaggerated. Finally, the data used in the curve are derived from an area sufficiently wide to eliminate in large measure the effects of purely local phenomena. Most of the trees grew within a circle 10 miles in diameter centering between Hume and the General Grant National Park, but a considerable number came from the Tulare region, where they were distributed in two tracts 8 miles or more from one another, and 60 miles from the main area. These trees from the Tulare region give curves whose main outlines are the same as those from the other area. Therefore it seems that local circumstances other than variations of climate have not had any noticeable effect upon the main form of the final curve.

In order to obtain exact results it is necessary not only to have a large number of measurements, but to determine all possible sources of error and make allowances for them. In addition to the corrections for age and longevity, which have been described in the preceding chapter, three other types of correction are needed. The first of these is a correction to offset the errors in counting, which are inevitable if the counting must be done by fallible human beings. Next a correction is required to offset the fact that the trees, as has already been said, do not always form complete rings each year, and so in some cases seem to be younger than they really are. Finally, the fact that the trees flare at the base, together with the fact that it is necessary to select the best rather than the average radii, demands still another type of correction.

In order to find out how large a part the individual idiosyncrasies of the various observers have played in causing errors of counting, I instructed my assistants to make a recount of a number of measurements. Unfortunately I did not realize the necessity of this until after I had left the field, and so my own error and that of four assistants, each of whom made a small number of measurements, could not be determined. For the three assistants, however, who with myself did four-fifths of the counting, and measuring, the statistics are sufficient to show the nature and degree of the errors involved. The method was simple. After one observer had finished a radius, he was instructed to go over it again and count the number of rings, and his two fellow-observers were instructed to do likewise.

Table 4 shows the result. In each case the number of radii involved is 46 and the average age is 1,472 years. The first column shows the age of the trees according to the original count. The other columns show the extent to which the recounts of the three observers, X, Y, and Z, differed from the original. It will be seen that in 22 cases, or nearly half, X obtained the same result as in the original count, which in many cases was made by himself. In 16 cases he obtained more than the original, his greatest divergence being 61 on a very difficult tree with small, almost invisible rings, and his average divergence being 10.1. In the remaining cases, 8 in number, he got less than the original, his worst result being −47, and his average −12.6. His divergences on the plus side exceeded those on the minus side by only 60, so that his average difference from the original was


A

only +1.3 years. If the sum of all his divergences, whether plus, minus, or zero, be taken it amounts to 262, or an average of +5.7. This is a trifle over 0.333 per cent of the average age of the trees. The net result is that in these 46 measurements, which are a

TABLE 4.—*The effect of recounting the rings of growth upon the apparent age of the sequoias of California.*

Number of tree in table.	Age per first count.	Difference between first counts and recounts of three observers.			Difference between readings A and B of tree.†
		X	Y	Z	
371 A....	1262	0	− 2	0	1
B....	1263	0	− 2	− 5	
372 A....	1453	0	− 8	− 1	1
B....	1452	0	− 8	− 6	
373 A....	1680	0	+ 22	+ 22	4
B....	1676	+ 20	+ 17	+ 26	
383 A....	1414	+ 2	0	− 8	44
B....	1370	+ 22	+ 13	0	
369 A....	1226	+ 61	0	+ 76	141
B....	1367	− 47	− 25	0	
410 A....	1893	0	− 31	− 20	51
B....	1842	0	+ 9	+ 20	
420 A....	1586	+ 2	− 5	− 2	21
B....	1607	0	.....	− 5	
*C....	1450	.....	− 10	.....	..
426 A....	1469	0	− 3	− 3	16
B....	1453	+ 10	+ 13	+ 9	
413 A	1289	− 4	− 14	0	4
B....	1285	+ 2	− 2	0	
417 A....	1284	+ 2	+ 3	0	4
B....	1288	+ 2	− 1	+ 9	
415 A....	1605	0	− 38	− 2	8
B....	1613	− 6	0	+ 11	
416 A....	1626	0	+ 11	− 10	9
B....	1635	+ 2	0	+ 7	
429 A....	1296	0	+ 4	+ 6	11
B....	1285	+ 18	+ 10	+ 19	
431 A....	1041	+ 1	+ 2	0	13
B....	1018	+ 3	+ 2	0	
427 A....	1690	0	+ 5	+ 1	0
B....	1690	+ 2	0	+ 6	
432 A....	1349	− 1	+ 2	0	1
B....	1350	− 1	− 4	0	
433 A....	2166	0	− 1	+ 7	11
B....	2225	0	+ 6	+ 13	
434 A....	2170	− 18	0	0	19
B....	2150	− 18	− 23	0	
436 A....	1525	0	+ 1	− 1	2
B....	1523	0	− 9	+ 3	
437 A....	1088	0	+ 3	+ 12	7
B....	1095	0	− 5	+ 3	
438 A....	1462	0	0	+ 3	41
B....	1452	+ 10	+ 15	0	
419 A....	1127	0	+ 17	+ 1	20
B....	1138	− 6	0	− 4	
428 A....	1270	+ 2	− 7	0	10
B....	1289	0	− 23	− 24	
Total........	69487	+161 −101 ±262	+155 −221 ±376	+266 − 92 ±358	439
Average......	1478	± 5.7 + .13	± 8.2 − 1.7	± 7.5 + 3.8	19.1
Grand average	1478		± 7.1 + 1.1		19.1

* This measurement was made by mistake at a part of the tree where a portion of the outer rings had decayed. Of course it was not used, but it is added here merely to illustrate the dangers that must be guarded against.

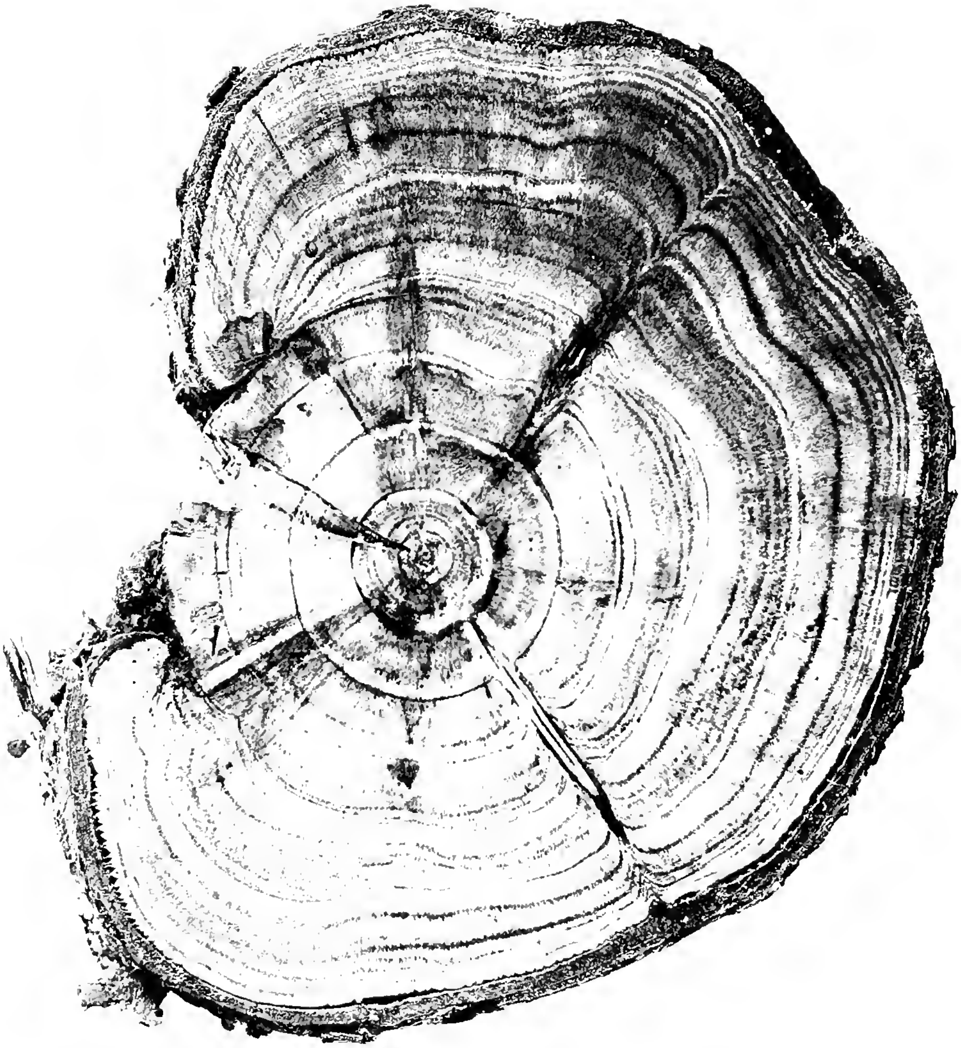
† This means the difference between the apparent age of the tree on the first count along two different radii as indicated by the numbers 1262 for 371A and 1263 for 371B.

fair sample of all, the probable difference between X's recount and the original count of himself or of one of the others was only 0.333 per cent, and might be either an excess or a deficiency, with a slight tendency toward getting more rings in the recount than in the original count. This tendency, however, amounts to only 0.1 per cent. With Y the case is similar, but as he was more careless than his two companions his divergence is greater, 8.2 years on the average, and he gets slightly less rings than they, as is shown by the fact that his average divergence when plus, minus, and zero years are added, comes out a minus quantity. In the case of Z, greater carefulness than with either of the others is indicated by the fact that on the average his recounts are 0.25 per cent more than he and his companions obtained in the original counts. In all cases the errors are so small that they can be neglected without serious consequences.

So far as mere errors of counting are concerned, it is probable that in the long run where a number of observers are concerned they balance one another; but there is still a certain degree of error on account of the fact that certain rings are so small that they almost coalesce and are not differentiated, but counted as one. This is evident from the fact that in general the more carefully a radius is prepared and the more minutely it is scrutinized with a lens, the greater the number of rings. As a partial offset to this may be put the fact that occasionally two rings are formed in a single year. Such cases are rare, however—far more rare than in the yellow pines examined by Professor Douglass—and it is almost invariably easy to distinguish them by the lack of firm, hard fiber in the outer portion of the extra ring, that is, the part which grows late in the season. On the whole we may conclude that, so far as purely human errors of counting are concerned, individual cases of very bad trees may occasionally run as high as an error of 5 or 6 per cent, but on the whole they are less than 0.333 per cent, and tend to balance one another, even with a single observer, and still more where several are concerned; yet there remains a certain error, slight, but constant, due to the fact that rings which actually exist are not counted. We have no means as yet of knowing how great this is, but it must be less than 1 per cent and probably not over 0.1 per cent, for in many trees all the rings are so large that one can not possibly fail to see them.

The next source of error, the actual absence of rings, is a much more serious matter than the errors of counting. When radii on different sides of a tree are counted they are in many cases found to be unequal. The table of recounts on page 145 shows that in the 23 trees there recorded the differences between the first and second readings range all the way from zero to 141, with an average of 19.1, or 1.3 per cent of the average age. In one exceptionally bad case a radius on one side of an old tree when first counted gave an age of 3,067, which when recounted was reduced to 2,996, while a radius nearly at right angles to the first gave an age of 2,587, which a recount reduced to 2,526. Such a divergence of 480 between the pair of readings made at the first attempt and 470 between the second pair is most unusual. It indicates great irregularity, and this irregularity, in turn, partially explains the large differences of 2 or 3 per cent between the original counts and the recounts, differences also due partly to the peculiar way in which the stump had been cut into the form of a rough cone and had since decayed to an uncommon degree. An inspection of the tables at the end of the volume shows that differences of 1 to 5 per cent between different sides of the same tree are not uncommon. Fortunately they are far from being the rule, since more than half of the trees show apparent differences of less than 1 per cent, which may be due in many cases to errors in counting. In the cases where there is a genuine difference it appears to be due to the fact that during bad years one side of a tree may not make any growth. This may be due simply to the fact that that side is shaded by other trees or is prevented from getting much nourishment because of the presence of great numbers of roots of other plants; or it may be due to injuries such as the breaking off of branches or the ravages of fire.

Plate 6 illustrates an extreme phase of the matter. When the young sequoia there shown was about 23 years old the portion about an inch to the right of the letter A ceased to grow for three or four years, while the opposite side grew as rapidly as ever. Then the stunted side revived and made a good growth during the last three years before the tree was cut. If the tree had continued to live it would doubtless have put on wood on all



sides, but the lost portions between the twenty-third and twenty-seventh years would never have been replaced. Should such a tree reach the age of 3,000 years, it might well appear 500 years younger on one side than the other. In a case like that of Plate 6 it is an easy matter to perceive the loss of the rings, but when a tree becomes large and the rings are not only very thin, but have a length of from 20 to 100 feet, as seen on the stump, it is extremely difficult to follow an individual ring and see whether it dies out or is continuous. Occasionally one can perceive ring after ring dying out, as is illustrated at A in Plate 6. At other times this can not be seen, but as the stump is counted farther and farther toward a given side the number of rings keeps increasing. In still other cases the loss of rings is manifest enough and makes no difficulty. This is true in cases of injury, such as burning. It is illustrated in Plate 7, where the rings are seen to tend to grow out from either side over the injured portion until finally they coalesce and the scar is no longer visible on the surface, although it still shows when the tree is cut. Where such scars exist it is always possible to avoid them in measuring, but in trees which have been subjected to many injuries, in order to avoid them, the measuring must be done upon lines which zigzag. In such cases the rings vary in width more than would be the case if only climatic causes were active. Such trees were in general avoided in our measurements, although a few were included, because they were of unusual age. Trees which have lost rings in the other, less noticeable fashion can not so easily be detected or avoided, inasmuch as two counts are necessary before their character becomes evident. Even then one can not be sure that the error is really in the tree and not in the observer until a third count has been made. Cases where three or more counts proved highly divergent were rejected in our final computations. Usually, however, a fair degree of agreement was found. In the majority of cases the first two readings were in such close agreement that both could be used. Nevertheless, differences of 1 or 2 per cent are common. In such cases we have assumed that the larger value comes nearer to representing the true age.

From what has just been said, it is evident that while many trees have the full number of rings on all sides, many others show deficiencies. Hence it is impossible to be sure of the exact age of any tree unless measurements are made on all sides. With trees having a diameter of 10 to 20 feet or more, and numbering their rings by the thousand, this is practically an impossibility because of the expense and time involved. If a small number of measurements, one, two, or three, are made upon each tree at places determined by the accidents of cutting and of smooth, clean, easily read radii, there is bound to be a deficiency in the apparent as compared with the real age of the trees. In individual cases the radii having the maximum number of rings will happen to be counted and the true age will be obtained. In the best trees, those which do not have the habit of dropping any rings, this will happen continually. With the other trees it will happen only rarely, and thus in any large group there is sure to be an error. This error can not be calculated exactly, since there is no known rule as to how much of a given ring is lost and how much retained. If we make an assumption as to this matter, however, the rest can readily be calculated. Let us assume that conditions are like those in figure 34. Here the age of the tree is supposed to be 100 years. In the half of the trunk indicated by the letters A^1, A^2, and A^3 all the rings are complete. In the other half they die out at regular intervals, until the minimum is reached at B, half-way between A^1 and A^3, the two points where the maximum comes to an end. This will be readily seen from the diagram, where the number of rings at the minimum is assumed to be 76. Suppose, now, that only one radius were measured in an infinite series of trees of this kind. This radius would fall at all possible positions, as chance might dictate. Half of the time it would have the maximum value of 100 rings. During the rest of the time it would vary from 100 to 76, with an average value of 88. Hence the average of all the readings would be the mean of 88 and 100, or 94, which is less than the true maximum by 6, or by one-fourth of the difference between the true maximum and the true minimum. Expressed in general terms this means that if half of the trunk has the full number of rings, and if the number diminishes regularly to a minimum at a single point, an average measurement will be less than the maximum by one-fourth of the difference between the maximum and the minimum.

Suppose now that two radii be measured and that the angle between them be 180°—that is, suppose that they lie opposite one another; in this case one of the radii will always have a value of 100, so that the average value of the apparent maximum will be equal to the true maximum. The value of the minimum, on the other hand, will fluctuate between 100 and 76, and its average will be 88.

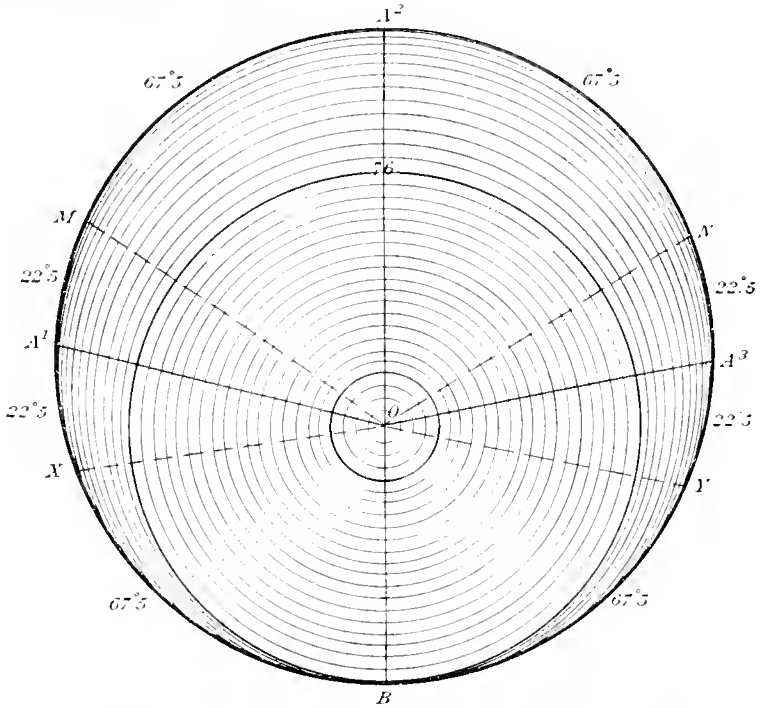


Fig. 34.—Ideal Diagram to Illustrate the Dropping of Rings.

In actual practise, where two measurements are taken, it is not possible to have them in line with one another. This is due to the fact that the trees, as has already been explained, are not sawed entirely, but are chopped through half their thickness. Only the sawed part can be measured with ease and accuracy. Hence, in the choice of places for measurement, we are limited to 180°. The distance of the radii from one another varies from 90°, or occasionally even less, up to 180°, according to the exigencies of the trunk in question. On an average, the distance is about 135°. In such a case, it is evident that the two radii will be equal when they lie anywhere in the portion of the tree $A^1A^2A^3$, or in the positions *XO* and *YO* at a distance of 22.5° from the line where the number of rings ceases to be the maximum. Evidently the maximum line can never lie in the sector of the tree, 135° in extent, between *X* and *Y*, but must lie somewhere in the sector XA^2Y. This part consists of 180° having a value of 100 and 45° whose value ranges from 100 to 94. The average value of this latter portion is 97. Therefore, the average value of all the maximum radii which could possibly be obtained when the two radii are 135° apart would be 99.4.

The value of the minimum radii may be calculated in the same way. Manifestly, the minimum can never lie in the portion of the tree MA^2N, but must lie in the portion *MBN*. The average value of this latter portion amounts to 90.4. The difference between the average maximum and the average minimum readings is 9, which is 9 per cent of the true maximum—that is, of the actual age of the tree. By comparison of the first and second readings of the trees actually measured, it is easy in any given group to compute this difference between the average maximum and the average minimum. Its value for all our sequoias is shown in table 5. There it will be seen that for trees under 1,000 years old it amounts to about 0.73 per cent. As the trees grow older it increases, until with trees more than 2,000 years old it becomes 1.62 per cent. Thus it appears that as a tree grows older the liability to loss of rings increases, so that a tree 2,000 years old is not only likely to have lost twice as many rings as a tree 1,000 years old, because it is twice as old, but this loss is likely to have been doubled. This greater proportion of loss among the old trees is due, apparently, to the fact already discussed, that the trees which live to a great age grow slowly in their youth. They are hard, knotty trees, able to resist drought, and perhaps not suffering by the loss of a year's growth so much as do trees which grow rapidly.

TABLE 5.—*The difference between the first and second measurements of sequoias.*

Age of trees in years.	Average age of trees in years.	No. of trees.	Difference between first and second measurements.		
			Sum.	Average.	Percentage of average age
A. 250–1000	640	115	536	4.65	0.73
B. 1000–2000	1470	257	4202	16.35	1.11
C. over 2000	2285	79	2914	36.90	1.62

The percentages given in table 5 enable us to form an estimate of the degree of accuracy which we have probably obtained in determining the age of our trees. If we assume that half of each tree, on an average, shows the correct number of rings, the ratio of the percentage of rings missing to the average difference between the maximum and minimum measurements will be 24 to 9. In group A of the table, the average age of the trees is 640 years. The average difference between the first and second readings amounts to 0.73 per cent. From this we can deduce the equation, $24 : 9 :: X : 0.73$. In this case, X is the percentage of difference between the absolute maximum and absolute minimum of the trees in group A. Its value is 1.94 per cent, and this percentage of 640 equals approximately 12 years. This means that, according to the assumption made above, the average tree under 1,000 years old misses 12 rings at some point in its circumference.

In order to find how nearly the supposed maximum approximates the actual maximum, another equation is necessary. In the assumed case of figure 34, the average maximum amounts to 99.4 per cent of the absolute maximum, and is less than it by 0.6 per cent. The difference between absolute maximum and absolute minimum is 24. The ratio of 24 to 0.6 equals that of 12 to Y, in which Y is the number of years by which the average measured maximum in trees under 1,000 years of age is less than the average absolute maximum. Y, it will be seen, amounts to 0.3, or less than half a year.

In the same way it is possible to calculate the number of years by which the maximum reading of trees of any age will be less than its true value. Even in the case of the oldest group of trees this amounts to only about 4 years, or 0.166 per cent of the age. This is so small a number that it can be neglected, and in cases where two or more readings are available we can assume that the error arising from the loss of rings is no greater than the error due to mistakes in counting.

Where only one reading is available, however, the case is quite different. In the ideal case of figure 34, an average reading is 6 per cent less than the true maximum; 6 per cent is two-thirds of the 9 per cent which we have seen to be the average amount by which the maximum and minimum readings differ from one another if the two lines of measurement be 135° apart. If we apply this ratio to the percentages of table 5, we find that in trees under 1,000 years of age the average reading is less than the true maximum by 0.48 per cent, while in the oldest group of trees it is less by 1.08 per cent.

From this it appears that if we would obtain correct results from our measurements of trees, it is necessary to make a slight addition in those cases where only one reading is available. The amount of this addition can be seen in tables C and D, on pages 302–307. It varies from a negligible quantity with the youngest trees to as much as four or five decades with the oldest trees. In making the computations upon which our final tree curve has been based, additions of this sort have been made—that is, in cases where only a single measurement of a tree was available there has been added a sufficient number of decades to bring the age up to the maximum, according to the assumption just set forth. The extra decades have been inserted at equal intervals from beginning to end of the tree's life. They have in every case been given the mean value of the decades on either side of them.

In addition to this, decades have been added to certain measurements for another reason. Where two or more measurements of a single tree are available I have assumed that the maximum reading is nearly correct, and have added enough decades to the other reading or readings to bring them to the same age. The decades have been distributed evenly from beginning to end of the tree's life, as in the other case. Where the difference between the readings amounts to more than 2 per cent, only the maximum reading has been used.

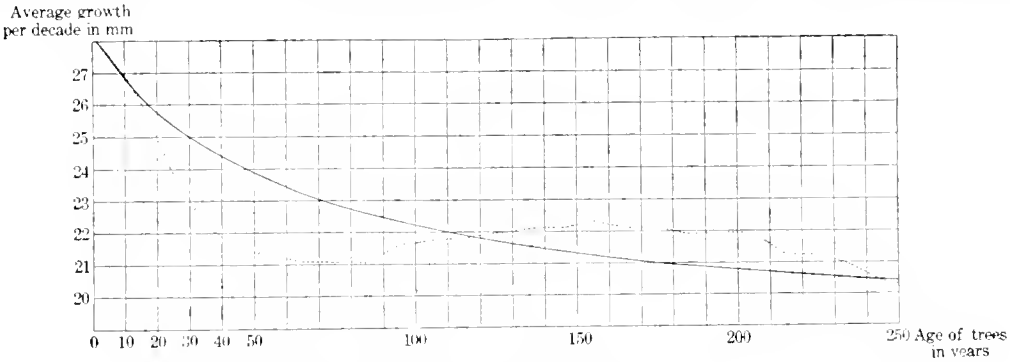


FIG. 35.—*Sequoia washingtoniana:* Corrective Factor for Age during first 250 Years of Life, plotted by Decades. (See Table A, p. 301.)

The object of all these changes is to give each tree its correct age as nearly as possible and to prevent the curve from flattening out. Suppose that a period of rapid growth took place in a tree 2,000 years ago and lasted two or three decades; if one measurement of this tree gives it an age of 2,500 years and another measurement gives only 2,450, or 2 per cent less, it is clear that the period of rapid growth 2,000 years ago, as indicated by the two radii, will come earlier in one case than in the other. The result will be that when the two are averaged it will not be so evident as it ought, for by being spread over a long interval it will be reduced by half its value, and will, in turn, raise places which ought to be low.

From what has been said in regard to this correction for missed rings, it may appear as if by applying it we should introduce large changes into our final curve; but as a matter of fact the total number of decades added to all the 785 measurements of our 451 trees amounts to only 405. The total number of decades indicated by all the measurements of these trees is 111,700, so that the total change in the curve amounts to less than 0.4 per cent. The maximum effect is, of course, produced in the oldest trees. The part of the curve less than 1,000 years of age is practically unaffected. From that point backward, the effect increases, but even at 2,000 years of age it amounts to only 8 years; a maximum which, according to the uncorrected curve, would occur at 100 B. C., according to the corrected curve occurs at 108 B. C.

The corrections for age and longevity are very different from those that we have just been considering. Instead of producing a small and almost unnoticeable effect, they greatly change the form of the curve. The methods used in obtaining them have already been considered. The diagrams shown in figures 35, 36, and 37, together with tables A, B, and G, on pages 301 and 323, demonstrate how these factors have been obtained and applied in the case of the sequoia. Little need be said of them except to call attention to one or two peculiarities. It will be seen that in figure 35, showing the average rate of growth by centuries, the curve is very regular from 600 to 1800, but that after that, when the trees begin to be old, it rises. This may imply that, whereas trees which are to live to great age grow slowly during their youth, when they get to old age they grow rapidly. Possibly this is because when the trees reach the ordinary age-limit of the species most of the individuals which had been growing with them die, and only the few old specimens are left. It is the habit of the sequoia to grow in groups, oftentimes half a dozen trees of the same age forming a circle. Frequently a tract of many acres is covered with trees of practically the same age. While a large number of them are alive, they naturally hinder one another's growth, but when most of them attain an age of 1,700 or 1,800 years—their three score and ten—the majority die. Then the few that are left have all the sun and soil and rainfall, and may be expected to grow more rapidly than ever before, or, at least, more rapidly in proportion to their age. It is possible, however, that a part of the apparent increased growth of old trees may be due to another cause, which will be discussed when we come to take up the correction for flare and for buttresses.

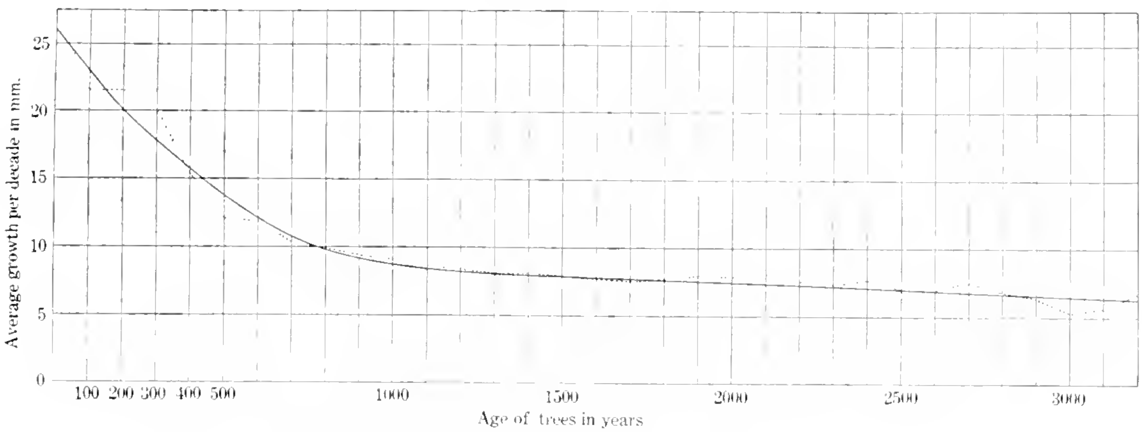


FIG. 36.—*Sequoia washingtoniana:* Corrective Factor for Age, plotted by Centuries. (See Table A, p. 301.)

The other of the two main corrective factors, that for longevity, can not be obtained without a large number of trees. The 450 sequoias available serve to make it fairly accurate, but not wholly so, for in the corrected curve shown in figure 38 the early parts have been depressed too much. The growth of the various groups of sequoias for different periods of their lives is shown in figure 37, and it is evident that the older trees in their youth, and to a less extent in their maturity, grow decidedly less rapidly than do those which do not live so long. From the five curves given in the upper part of figure 37 it would perhaps be possible to deduce corrective factors applicable to each group and to each decade of the life of each group. This would involve so much risk of error, however, that I have not done it. Instead I have obtained the average growth of each group during the first 1,000 years of its life (provided, of course, it lived so long) and have plotted this in the broken line at the bottom of figure 37. Through this has been drawn a smooth solid line which I have used as the basis for the corrective factor for longevity as given in Table B, page 301. No correction is applied to the nine youngest groups, and a single factor is used for all of the six oldest groups. To this is probably due the fact that the early parts of the curve of figure 38 fall unduly low. As has been already indicated, the purpose of the main corrections, excepting that for absence of rings, is to reduce the curve of tree growth as nearly as possible to a straight line by eliminating all effects except those of climate. This process has been carried so far, especially by the corrections for age and longevity, that we have apparently eliminated and even reversed certain differences between the remote past and the present which are really due to a difference in climate. The reader can not be too strongly reminded of this fact. The curves of tree growth as here presented show with great exactness the cycles which are of less duration than the periods covered by the curve; but they do not show the possible differences that may exist between the mean climate of the present and of 3,000 years ago.

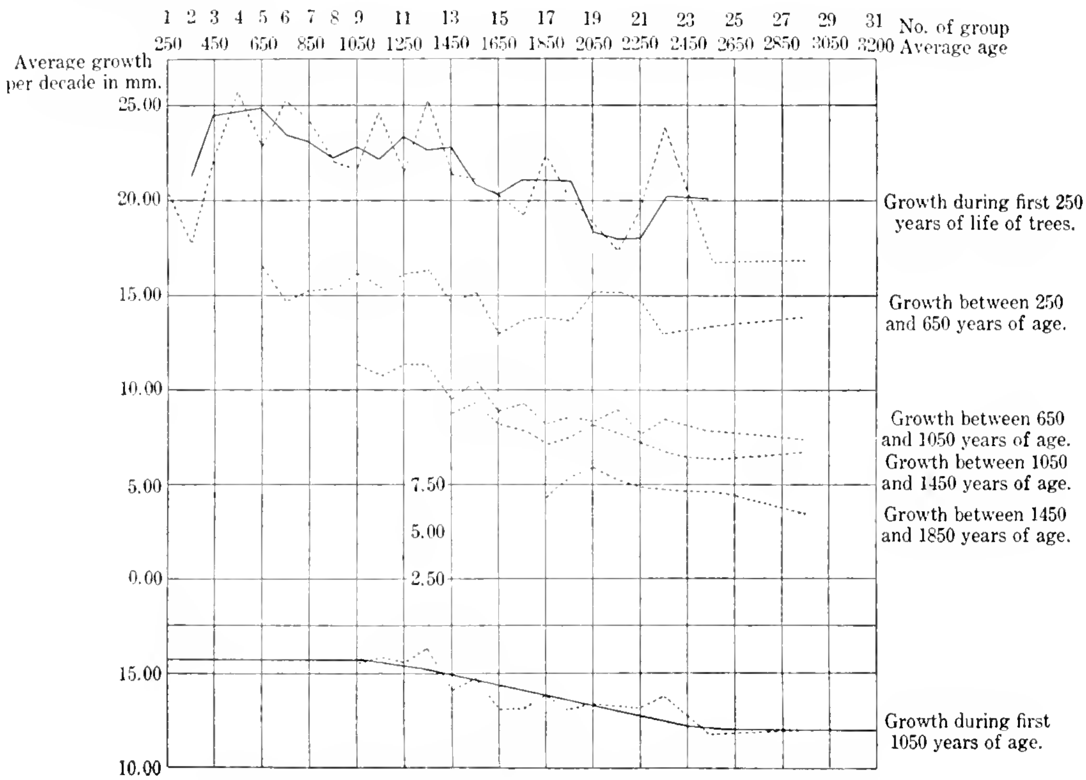


FIG. 37.—*Sequoia washingtoniana*: Corrective Factor for Longevity.
(See Table B, p. 301.)

An examination of the curve of the sequoias corrected for age and longevity, the solid line of figure 38, shows that as a whole it rises from left to right in a quite unexpected fashion, especially in the later or right-hand portions. Just where the most marked rise begins it is hard to say, but from about 1200 A. D. onwards it is plainly visible, and from 1500 A. D. onward it is highly marked. This rise in the curve seems at first sight to indicate that the climate of California has been growing distinctly moister during the past 600 or 700 years, which would be most interesting and important if it should prove to be a fact. Yet other evidence points in the contrary direction. In the first place, the major changes in California, as distinguished from the minor ones, appear on the whole to agree with those in New Mexico and Arizona, and in that region there are strong indications of greater aridity at present than during long periods in the past. In California itself there is not much evidence on this point. Yet the distribution of young sequoias is too important a matter to be overlooked. In three different localities, during the summers of 1911 and 1912, we investigated the number of young sequoias as compared with old, and as compared with the number of young trees of other species. We found that young trees are abundant in moist places, such as valley bottoms, the flat tops of ridges, and hollows where moisture accumulates at certain times or where it runs slowly through deep soil; their number, however, is never so great as is the case with other trees, such as pines, firs, and cedars, but this is natural, since a tree whose span of life is so long as that of the sequoia does not need to reproduce itself rapidly. The number of young trees is quite sufficient to prevent the extinction of the species and to insure that 1,000 or more years from now these moist places shall have as many sequoias as they have to-day. (See Plate 5, page 139.)

On dry slopes, however, the case is quite different. In some places we searched and searched, in the hope of finding young trees. There were plenty of mature ones, 500 or 1,000 years old or more, but practically no little ones. Now and then a seedling or a young tree 3 or 4 years old was found, and once in a while we came upon large groups of these which had just sprung up. Between this age, however, and an age of many hundred years, it was almost impossible to find a tree. Young trees of other species abounded wherever an old tree had died and given an opportunity, and there were pines, cedars, and firs of every age, from seedlings to those that were dying of senility. Actual count showed that the number of young trees was many times in excess of that of old ones, and that the

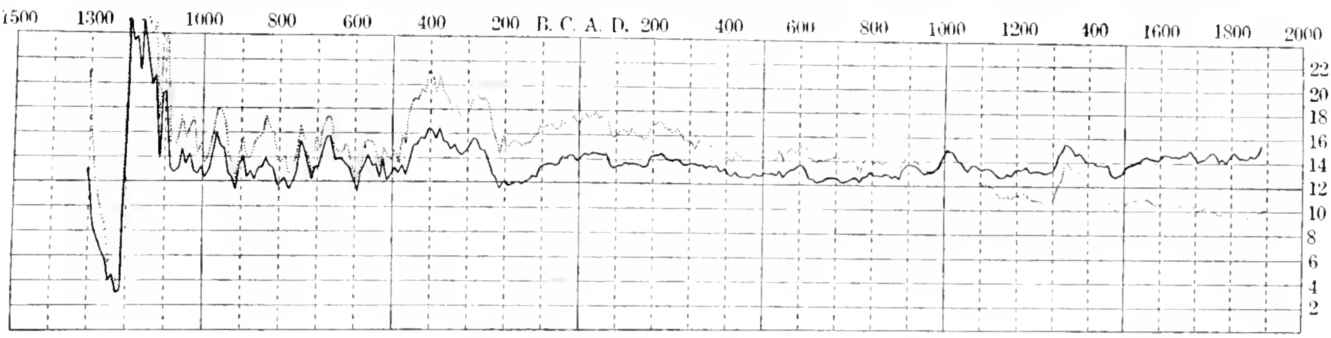


FIG. 38.—Curve of Growth of the *Sequoia washingtoniana* in California. Uncorrected (. . .) and Corrected (——). (See Table E, pp. 308–310.)

number decreased gradually in proportion to the age. With the sequoia, however, no such thing was true. Often the number of young trees was actually much less than that of old ones. If the trees in the future reproduce themselves no faster than they have during the past 500 years or more, the species will ultimately become extinct upon these slopes. Seeds are apparently able to sprout during moist years, and to grow as long as the rainfall continues propitious, but as soon as dry years come the little trees die. Thus the sequoia in the dry parts of the forest has not been able to reproduce itself, although in the moist parts it holds its own. Apparently the average conditions extending over centuries can not be the same now as in the past. If they were, young sequoias ought to be abundant. The only explanation of the absence of young trees seems to be a change from the past to the present.

In the face of this stands the curve of figure 38, as it appears after the corrections for age and longevity have been applied. At the end of our first season's work, when the curve for the trees measured that year was plotted, I confess that I was greatly puzzled. The evidence of the curve seemed too strong to admit of doubt; but at the same time the absence of young trees on the dry slopes where the old ones flourished, together with the abundant evidences of desiccation in other parts of the world, also seemed too strong to doubt. On returning to the Sierras a second time, however, in 1912, the difficulty soon solved itself. Two things have a share in causing the growth of recent centuries to appear greater than it really is. One of these is the form of the trunk of the sequoia, and the other our choice of places for measurement. The sequoia habitually grows with a round, smooth trunk which maintains its thickness well up to the top, so that for long distances the diameter varies only at a very slow rate. At the base, however, as soon as the trees become of any considerable age, the trunks flare and send out buttresses. The woodsmen who fell the trees naturally prefer to do their cutting at a point above the flaring portion, and thus save themselves the work of cutting through the extra thickness. In the case of young trees, not over 1,000 years of age, this is feasible, although it necessitates the building of a platform at a height of 6 feet or so above the ground. In the case of older trees the amount of flaring is so great that it is impracticable to avoid it unless the trees are cut at a height of 15 or 20 feet. When the lumbering of the sequoias was first begun, this was sometimes done, and in order to climb to the top of certain old stumps we were obliged to throw ropes over them and clamber to the height of a second-story window.

In later years, however, the practise has been to cut the trees low. Some of the best and oldest stumps are cut not more than 3 or 4 feet from the ground, and 5 or 6 feet is the ordinary height. In the flaring portion of a trunk the arrangement of the rings, as it appears in a vertical section through the middle, is illustrated in figure 39, where it will be seen that the central rings—those which grew while the tree was young—are vertical and the line of cutting is at right angles to them; but the later rings have a distinct slope parallel to the flare of the tree. Hence, when they are cut horizontally by the saw of the woodsman, as indicated by the solid line *AB*, they are not transected at right angles. Thus their apparent width, as seen on the surface of the stump, is greater than their real width, as shown in the dotted lines. In a few special cases we were able to make allowances for this and to measure the rings at right angles instead of horizontally; but in the majority of cases this was utterly out of the question. It would have involved so much cutting, so much extra time in measuring, and so much danger of making mistakes in counting and measuring, that not only would the number of trees that we could measure have been too small to give reliable results, but the character of the measurements would have been more open to question than is now the case. The only course seemed to be to measure horizontally and then to make corrections in the final curve.

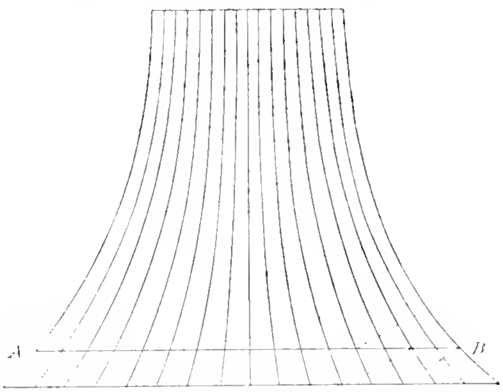


FIG. 39.—Effect of Flaring Buttresses on the Measurement of Rings of Growth.

The degree to which this flare at the base of the trunk is effective may be judged somewhat from table 6. This table is compiled from sections of wood cut from relatively young trees, for the purpose of making measurements of the growth during the last 50 or 100 years, by years instead of by decades. Trees having a diameter of not over 6 or 7 feet near the base and not over 600 or 1,000 years old were selected; yet even these relatively young trees flare considerably. Out of 85 specimens which happen to be at hand at the time of writing, I have selected the 32 which show this effect most clearly. A glance at the table shows that the horizontal distance along which measurements are made exceeds the actual distance at right angles to the rings by amounts varying from 3 per cent to 16 per cent, the average being 7.6 per cent. Out of the 85 trees, 32 others, while flaring noticeably, show a less degree of flaring—that is, 2 to 5 per cent—while 21 show the effect of flaring to the extent of 2 per cent or less, and may be considered practically straight. If the curve of growth of the 32 young trees whose flare has been calculated were plotted without further correction, the part belonging to the present time would be nearly 8 per cent too high in comparison with the earlier parts. With old trees this effect is exaggerated. From this in part comes the rise in the latter part of the solid line in figure 38.

TABLE 6.—*Effect of flare at base of sequoias.*

Field No. of tree.	No. of years available for measurement.	Horizontal measurement of section in mm. = A.	True thickness of section when measured at right angles to the rings = B.	Ratio of A/B.	Field No. of tree.	No. of years available for measurement.	Horizontal measurement of section in mm. = A.	True thickness of section when measured at right angles to the rings = B.	Ratio of A/B.
2003	64	83	73	1.13	3059	20	94	86	1.09
2007	54	99	94	1.05	3061	52	219	211	1.04
2014	?	186	174	1.07	3063	74	143	136	1.05
2016	105	126	114	1.10	3065	?	125	116	1.08
2021	74	175	166	1.05	3050	84	131	126	1.04
2029	99	165	152	1.08	3062	72	146	131	1.11
×	63	130	114	1 14	3069	86	122	116	1.05
3030	67	174	150	1.16	3077	71	173	159	1.09
3031	63	168	157	1.07	3078	52	123	119	1.03
3032	84	232	209	1.11	3080	63	112	105	1.07
3034	94	227	205	1.11	3085	71	142	133	1.07
3035	47	195	181	1.08	3082	114	142	137	1.04
3042	102	130	124	1.05	3087	50	179	168	1.06
3046	56	165	158	1.04	3091	63	192	185	1.04
3054	31	140	128	1.09	3090	54	177	165	1.07
3055	26	171	153	1.12					
3057	28	200	190	1.05	Total.....	1983	....	....	34.43
					Average...	64	....	....	1.076

Still another factor produces an error in this same direction. As the trees get older they tend to throw out buttresses at the base. In the center of the buttresses the rings of growth are well developed, wide, easily measured and counted, and are rarely missing. In the portions between the buttresses they are thinner, more crinkled and hence hard to measure, and are more apt to be missing than in the neighboring buttresses. When the tree is younger and there are no buttresses, the rings preserve nearly the same width throughout the entire circumference, and a measurement in one place is as good as in another. Where the buttresses exist, however, a measurement along them gives an impression of growth greater than is warranted by the facts. If the buttresses and the depressions between them are averaged together, the average growth of an old tree appears to be distinctly less than where the buttresses alone are measured. It would be possible to avoid a part of the error due to buttresses by choosing only young or uncommonly symmetrical trees which flare but little. We were confronted, however, by the paramount necessity of finding as many old trees as possible; therefore we felt obliged to take every tree of great size which gave promise of giving fairly accurate measurements. The errors involved in measuring along the buttresses are less serious than those which would have arisen had we measured along the hollows, where there was danger of losing a considerable number of rings. After the danger of the buttresses was realized, we tried, so far as possible, to take our measurements from points half-way between buttress and hollow, but this in many cases proved impracticable, and we were thrown back upon the good, clean sections of the buttresses.

From what has been said above, it is evident that the corrected curve of growth of the sequoias, as given in figure 38, is wrong in two respects: (1) the early portions fall unduly low, partly because of scarcity of data and consequent imperfections in the correction for age and longevity, and partly because those corrections are deliberately designed to eliminate any effects due to a change of climate occurring in a cycle of 3,000 years or more; (2) the later part of the curve rises too high on account of the flaring buttresses at the base of the trunks of the trees. With our present incomplete data these two errors can not be eliminated by any strictly mathematical correction. The best that we can do is to adopt some standard unconnected with the trees, and swing the curve of growth so that at a few critical points the relative height of the two is the same, taking the greatest care, however, that we do not alter the sinuosities. For this purpose I have adopted the fluctuations of the Caspian Sea as given in Chapter XVII of the "The Pulse of Asia."

This involves anticipation of two conclusions which are to be discussed in the following chapter: first, that the sinuosities of the sequoia curve actually represent pulsations between aridity and moisture; second, that the pulsations in California have been essentially synchronous with those of Central Asia.

Assuming for the present that these two conclusions are valid, we may correct the curve of the sequoia. For this purpose, the following critical levels of the Caspian Sea have been taken as the standard:

Mean level 1750–1890 A. D. equals 0 feet.
Recorded high level in 920 A. D. equals +29 feet.
Estimated level below ruins now under water, in seventh century, −20 feet.
Estimated level about the time of Christ +85 feet.
Estimated level about the time of Herodotus +150 feet.

The historic and physiographic evidence in support of these figures is given in the chapter of "The Pulse of Asia" already referred to. On the basis of these levels of the Caspian Sea the curve of the sequoias has been tilted in such a way that the portions at the respective dates given above lie at heights approximately proportional to the height of the Caspian Sea at the corresponding dates. Further than this no change has been made. In applying this "Caspian corrective factor," the sequoia curve has been divided into four portions: (1) from the earliest times until 400 B. C., a portion which has simply been raised to correspond with the inferred level of the Caspian at 400 B. C. but has not been tilted because we have no knowledge of the sea in earlier times; (2) 400 B. C. to 400 A. D., which has been tilted in such a way that 400 B. C. lies 15 per cent higher than in the curve of figure 38, while 400 A. D. is unchanged; (3) 400 A. D. to 900 A. D., which is unchanged, and (4) 900 A. D. to the present time, which has been tilted so that the modern end of the curve lies 9 per cent lower than in figure 38. In addition to this I have arbitrarily made a slight reduction in the great maximum which culminates about 1000 B. C., but this is a matter of no importance. The exact extent to which the position of the curve has been altered in each decade is indicated in the column headed "Caspian Corrective Factor" in Table G, pages 323–324.

The resultant curve, given in figure 50 on page 172, represents the nearest approximation that now seems possible to the actual curve of growth of the sequoias as it would be if it were uninfluenced by differences in the rate of growth of old trees and young, or by any other influences except those of climate. Its further discussion will be deferred until we have considered the reasons for believing that the low portions indicate aridity, while the high indicate abundant moisture; but one vital point must again be emphasized: it may seem, perhaps, that we have taken liberties with our curve of growth and have altered it arbitrarily; but this is far from the case. Every alteration has been based on strictly mathematical considerations, and no assumptions have been made except at the very end, where the Caspian factor is used. Even so, nothing has been done to alter the location of the sinuosities of the curve. A comparison of the dotted line of figure 38 and the solid line of figure 50 shows that although many corrections have been applied, the essential features, that is, the ups and downs which appear to indicate climatic pulsations, have not been essentially changed either in position or in relative importance.

CHAPTER XIV.

THE INTERPRETATION OF THE CURVE OF THE SEQUOIA.

The rate of growth of the vegetation in any given locality varies from year to year, chiefly because of changes in precipitation and temperature. In northern regions, where there is precipitation at all seasons, temperature is probably the most important factor. Farther south, however, the amount of rain becomes of increasing importance. Professor Douglass has shown, as we have seen, that, in spite of all the accidents to which plants are liable, three or four yellow pines are sufficient to give a record of the rainfall in Arizona with an accuracy of approximately 70 per cent. This is true even where individual years are concerned. If we employ a unit of time longer than a single year, so that the stored-up moisture of the soil and energy of the tree have less effect, and if we base our conclusions on a large number of trees instead of a few, the agreement between rainfall and growth must become much greater than 70 per cent. It would seem, indeed, that with a time-unit of 10 years and with a number of trees amounting to hundreds the agreement ought to be over 90 per cent. This conclusion, however, is based solely on the yellow pine of Arizona. Before it can be applied to other species in other parts of the country, further investigation is necessary. In the Sierras, where the sequoias grow, the climatic conditions are in many ways similar to those of the high plateaus of Arizona, where the yellow pines have their habitat. The total precipitation in the sequoia region, however, is much greater than among the pines, perhaps twice as much. Moreover, there are no summer rains in California, which adds another element of difference. Yet in spite of the differences the two regions are sufficiently alike to cause us to infer that in both places trees of the same species would be similarly influenced by variations of rainfall. The introduction of a new species, however, may completely reverse matters. Hence we are not justified in drawing any conclusions as to the sequoia until we have made a comparison of actual measurements of the growth of the trees year by year with the precipitation at the nearest possible meteorological stations.

The rainfall of central California—that is, of the portion of the State lying west of the Sierra Mountains between latitudes 35° and 39°—varies enormously. In the southern part of the Great Valley near Bakersfield and the Kern Lakes it averages only 5 to 10 inches a year, and in no part of the valley does it rise much above 15 inches on an average, though in individual years it rises twice as high. In the Sierras at an altitude of 4,000 feet or more, and in the Coast Range at somewhat lower altitudes, it rises in some places to an average of 50 to 60 inches per year. In spite of this difference in amount, however, the proportional variations from year to year in different places are closely similar. This is evident from an inspection of figure 40, which represents the annual rainfall since records began to be kept at selected meteorological stations in various parts of central California. In view of the long, dry season in summer the precipitation is naturally reckoned from July to July rather than from January to January. The first curve represents the rainfall at Fresno. This is placed first because it is the one chiefly employed for comparison with the tree curves. The next curve shows the rainfall at Bakersfield, which lies in the southern part of the Great Valley and is selected partly because it lies well to the south and partly because, with an average rainfall of only about 5 inches, it is the driest place in the whole district. The next two curves represent Portersville and Tulare, which lie in the Great Valley, not far from the base of the Sierras, and have been selected because, being about 35 and 50 miles from Dillonwood, they are the nearest records of any considerable length available for comparison with the growth of the sequoias at that place. The next curve is that of Sanger, the meteorological station nearest to Hume, where most of our sequoias grew. If we continue to mention the curves in the order of geographical location, the next should be the one for Fresno, which is here plotted at the top. Since the record for Fresno goes back to 1881–82 while that for Sanger goes only to 1889–90, and since Fresno is only a little more distant from Hume than is Sanger, Fresno has been chosen for comparison with the

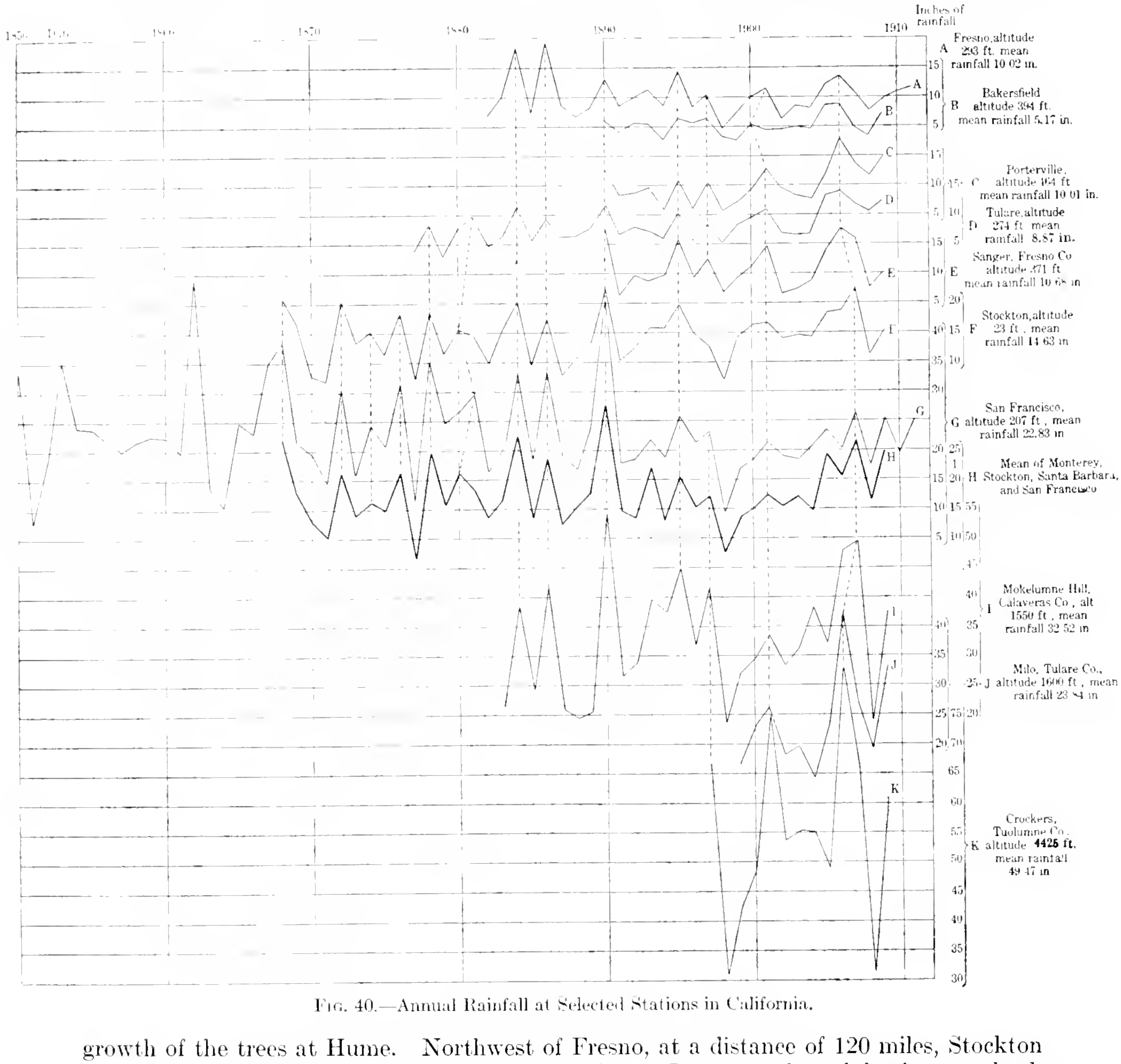


FIG. 40.—Annual Rainfall at Selected Stations in California.

growth of the trees at Hume. Northwest of Fresno, at a distance of 120 miles, Stockton lies in the Great Valley on the way to San Francisco. Its curve of precipitation goes back to 1867–68. It is chiefly important as a meteorological way-station between the sequoias and San Francisco. The next curve and all those below it are extremely jagged; for, although the rainfall of the places represented in the later curves ranges from 20 to 55 inches, instead of from 5 to 20 as in the preceding places, the same scale is employed for purposes of comparison. The curve for San Francisco is the most important, since it goes back with a good degree of accuracy to 1849–50. Below the San Francisco curve comes a closely similar one, showing the average rainfall for San Francisco itself, together with Stockton to the east of it in the Great Valley, and Monterey and Santa Barbara, which lie respectively 100 miles and 275 miles down the coast from San Francisco. These four places were selected simply because they possess meteorological records going back farther than those of any other towns in this region. Among the last three curves, the one for Milo, at an altitude of 1,600 feet in Tulare County, between Portersville and Dillonwood, has been selected not only because it is a mountain station, but because it is the nearest to Dillonwood. Unfortunately this record is very short. The other two curves, for Mokelumne Hill, at an altitude of 1,550 feet in Calaveras County, and for Crocker's, at an altitude of 4,450 feet in Tuolumne County, have been selected because, although these two places are respectively 100 and 150 miles northwest of Hume, they are almost the only available examples of the abundant precipitation which characterizes the mountainous regions in the vicinity of the great sequoia groves. All of them lie lower and have probably less rainfall than the habitat of the sequoias, but the conditions at Crocker's appear to be closely similar to those where most of the Big Trees are found.

Inspection of the eleven curves of annual rainfall in figure 40 shows that they agree closely as to their main features. The years 1868, 1872, 1874, 1876, 1878, 1884, 1886, 1890, and 1895 show maxima in every curve. The maximum of 1897 appears in all the curves except that for Stockton and that for 1901 in all except Bakersfield. Either 1880 or 1881 shows a maximum in every case, and both years are always above the average. Finally, either 1906 or 1907 shows a maximum in each curve. The minima agree quite as markedly as the maxima. In fact the annual distribution of rainfall in any of the less extreme places in central California may be taken as typical of the whole region. Thus a long record, such as that of San Francisco, may be used to give an approximate record for any other place, simply by multiplying the San Francisco values by a sum sufficient to change the mean value of the San Francisco record to the mean value of the other record for the same period of time. This process of "making up" records is in common use among meteorologists.

I am indebted to Professor Alexander G. McAdie, of the local Weather Bureau at San Francisco, for having made up a record for Fresno by comparison with San Francisco. The factor in this case is 0.47. In the comparisons of rainfall and tree growth that follow I have used this made-up record for Fresno for the period from 1850 to 1882, and the actual record from 1882 onward. I shall not refer to this matter again, but shall simply treat the combined made-up and actual records as if they were of equal value. The agreement between variations in rainfall from place to place applies not merely to the annual rainfall but also to that by months, although not to so great an extent. This is evident from figure 41, where the monthly distribution of precipitation for the 8 years beginning with 1889–90 and ending with 1896–97 has been plotted for Portersville, Fresno, and San Francisco. Inasmuch as the rainfall of San Francisco is more than double that of the other two places, it has been plotted on half as large a scale. Apart from what may be called accidental details, the general form of the three curves is similar, and the three curves for any one year resemble one another more than do the curves for any given place for three successive years. On the basis of the agreement here shown, it seems permissible to use the San Francisco record as the basis for a made-up record of monthly as well as annual rainfall for Fresno prior to 1882. I shall do this when we come to a discussion of the type of seasonal distribution of precipitation which most stimulates the growth of trees.

The actual comparison of the rate of growth of trees with the precipitation for the season beginning in July of the preceding year and ending in July of the year of growth is at first sight inconclusive and puzzling. Let us examine the matter in two separate cases.

The first is shown in figure 42, where the precipitation at Porterville is compared directly with the growth of young sequoias at Dillonwood between 30 and 40 miles to the east of Porterville and 6,000 feet above it. The measurements used in preparing the two curves of growth here shown consist of group A (46 measurements of 19 trees, none of which was over 100 years of age and most of which were less than 40 years of age) and group B (8 measurements upon 5 trees having an age of from 100 to 150 years). Several of the

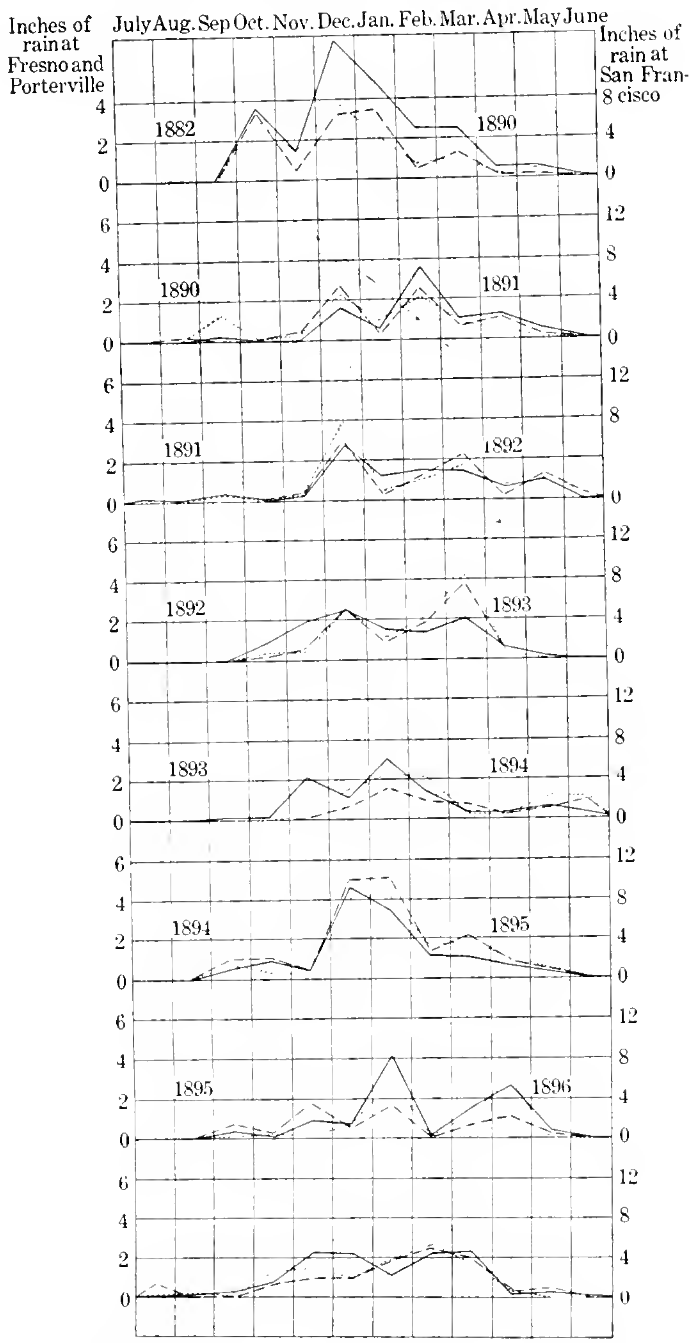


FIG. 41.—Monthly Distribution of Precipitation in California.

older trees were sickly and were cut by accident, that is, the purpose was to cut young trees, not over 100 years of age, but those of group B, having grown slowly, appeared younger than they actually were. Hence their curve is low and has few variations, but it agrees fairly well with that of the younger trees. Both curves have maxima in 1881, 1885, 1888, 1900, and 1903, and the maximum of 1907 in the lower curve agrees with a marked increase in growth in the upper curve followed by a maximum the succeeding year. A marked difference in the curves is seen in 1890, where the younger trees much increased their growth while the older trees remained practically stationary. This seems to mean that the very young and rapidly growing trees of group B were stimulated by the heavy rains of 1889 and 1890, while the older trees were unaffected. Apparently the stimulus given to the young trees gave them such vigor that its effects did not disappear for 15 years.

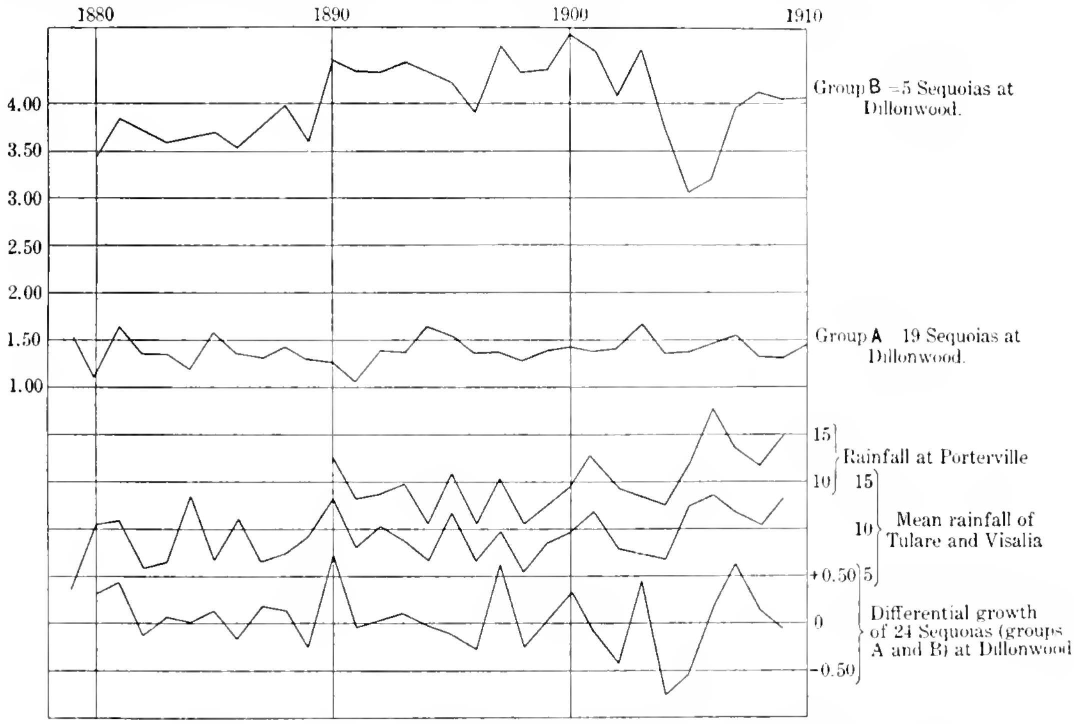


FIG. 42.—Rainfall at Portersville Compared with Growth of Sequoias at Dillonwood.
(See Table I, pp. 328–329.)

When the curves of growth are compared with the curves of precipitation it appears at once that they do not agree at all closely, nothing like so closely as in the cases cited by Professor Douglass; yet on closer examination it appears that there is a certain amount of agreement, although this is by no means noticeable. For instance, in 1881, 1890, and 1897 the curve for the larger number of trees—that is, group B—and the rainfall curves are both at a maximum. In 1895 the rainfall curve reaches a maximum, which does not appear in the tree curve, apparently because of the very dry year just preceding. In 1901 the rain is again at a maximum, and the tree curve is high, although the maximum growth was attained a year earlier. In 1905 and 1906 a marked disagreement is noticed, for in those years the rainfall was uncommonly heavy, while the trees grew uncommonly slowly. This seems to be due to the fact that the preceding years had been dry and therefore the growth of the trees had been much checked. In 1906 the rain at Portersville and Tulare did not come in great abundance until March, April, and May, during which months over 12 inches fell at Portersville instead of the usual 3.25 inches. Much of this, coming so late, ran quickly off, yet part of it was probably retained, and the way thus prepared for the rapid growth of the trees in 1907.

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Trees, like other living beings, possess much inertia. If they are subjected to favorable conditions for a few years and make a good growth, they are in a position to keep on in the same way unless seriously checked. Therefore, in estimating the effect which the conditions of an individual season have upon their growth, the actual amount of growth is less important than the change from preceding years. Accordingly I have added to figure 42 a lower line showing the differential growth of the trees at Dillonwood—that is, the amount of increase or decrease of growth compared with the year immediately preceding. This curve shows a fair degree of agreement with the curves of precipitation, but there are also disagreements, such as 1887 and 1903. Other factors besides the rainfall of the season immediately preceding the year of growth evidently have a large effect upon the trees. Moreover, our records of rainfall are derived from places 30 to 50 miles from where the trees were located. Nevertheless, in cases like 1881, 1890, 1897, 1900, and 1907, there seems reason to think that we can see the direct effect of the precipitation of the preceding winters. Yet in spite of this, these Dillonwood curves might be used almost as well to show that rainfall and tree growth do not agree as to show that they agree. They have been introduced here purposely in order to show the difficulties, and in order to emphasize certain facts which will be brought out later; namely, that the growth of the trees depends upon the rainfall of several years, and not of one year, and that it is influenced by the season at which precipitation falls quite as much as by the actual amount of precipitation.

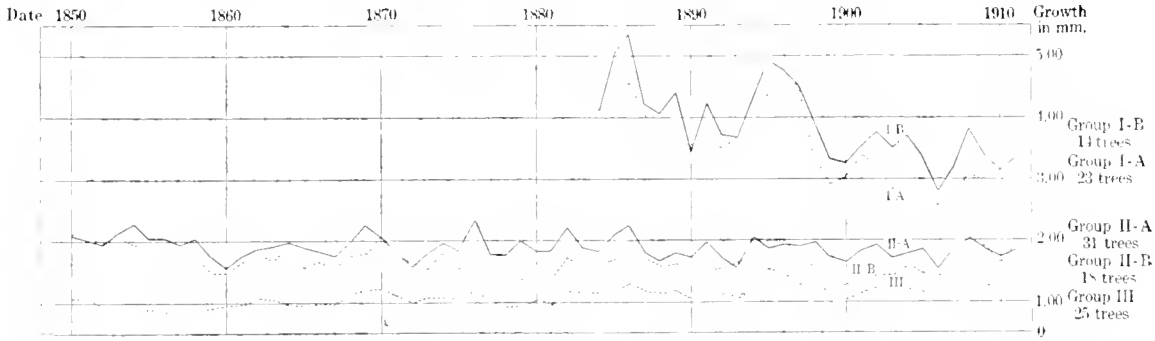


FIG. 43.—Annual Growth of 111 Sequoias at Hume.
(See Table I, pp. 328–329.)

It would be possible to go on and show more clearly the exact nature and degree of the effects produced upon the Dillonwood trees by past rainfall and by variations in its seasonal occurrence, but as only a small part of the measurements used in our final long curve of growth (extending back over many centuries) came from Dillonwood and the other regions near Portersville, it seems wiser to discuss the matter in relation to the trees at Hume. At that place I pursued a method somewhat different, and on the whole distinctly more reliable, than that followed at Dillonwood. Instead of cutting young trees, whose youth makes them particularly liable to be affected by accidents, I selected over 100 vigorous trees in early maturity; they were from 5 to 8 feet in diameter and had a probable age of from 500 to 1,000 years. The Hume-Bennett Lumber Company, on whose land they stood, kindly gave me permission to cut from them small sections 8 or 12 inches in length and showing the rings of growth for a period varying from 30 to nearly 200 years. The difference in the number of rings depends partly on the size of the sections, but it is far more largely dependent on the rate of growth of the trees, for a slow-growing tree of course shows many more rings per inch than does a fast-growing one. On the basis of the number of rings the 111 sections have been divided into three groups, and the first two groups have each been divided into two subgroups, one of which grew in wet, swampy places, and the other upon drier slopes.

The groups are as follows:

Group I. Sections showing 60 rings or less; trees of rapid growth: (*a*) From dry localities, 23 sections. (*b*) From damp localities, 14 sections.

Group II. Sections showing from 60 to 100 rings; trees of moderate growth: (*a*) From dry localities, 31 sections. (*b*) From damp localities, 18 sections.

Group III. Sections showing over 100 rings; trees of slow growth: (*a*) From dry localities, 25 sections. (*b*) From damp localities, no sections. (Trees in damp places almost universally grow rapidly.)

The uncorrected curves of growth derived from these five groups are shown in figure 43. The solid lines represent the trees living in damp localities, while the dotted lines represent those from dry localities. The trees in the swamps grow the fastest, as would naturally be expected, but in times of adversity they appear to be the first to suffer and are on the whole more affected than are those in the drier locations. Hence we conclude that, for a curve of growth possessing the highest degree of accuracy, vigorous, rapidly growing trees located in small swamps which are easily dried up are the most advantageous. The difference in the form of the various curves, however, is comparatively slight, except that the rate of growth in the successive groups is slower and slower. In general the curves show periods of maximum or increasing growth about 1850, 1854–55, 1862–64, 1868–70, 1876, 1882, 1886, 1894-96, 1902, and 1908, while periods of minimum growth are almost as markedly in agreement. If a time unit of 5 or 10 years were used instead of one year, and if the proper corrections were applied to eliminate the various errors due to age, longevity, and the like, the five curves would be practically identical. This supports the conclusions of Professor Douglass as to the possibility of obtaining fairly reliable records from a small number of trees. Nevertheless, there can be little doubt that much more accurate results are obtained where a large number is employed.

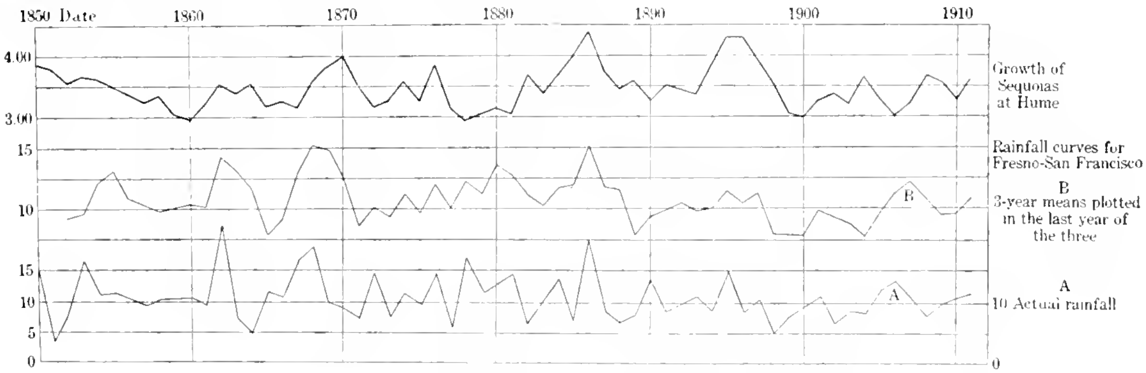


FIG. 44.—Growth of Trees at Hume, and Rainfall at Fresno.
(See Table I, pp. 328–329.)

We have now to determine how far the synchronous fluctuations in the rate of growth of these five groups of trees are due to variations in rainfall. The trees of all the groups are scattered over an area of about a mile square. No fires appear to have occurred in the region for many years, certainly not during the last 30 or 40, and probably not for centuries. The trees were all strong and vigorous at the time when the sections were cut, and there was no sign that they were influenced by any special diseases or parasites. They were scattered in all sorts of locations, from places where swamps or perennial brooks bathed their roots to dry, rocky hillsides subject to constant drought. Unless the variations in the rate of growth are due to climate, there seems to be no adequate explanation of their existence. Nevertheless, when the combined curve of the five groups is placed beside the curve of rainfall at Fresno and, before 1882, San Francisco, as is done in figure 44, the degree of agreement is scarcely so great as one would expect. The combined curve of the five groups is obtained by using all of the 111 trees as far back as 1884. At that point the

37 trees of group I are dropped and a correction is applied, as explained in a preceding chapter, in order to compensate for the difference between the average rate of growth of all the trees and that of the 74 trees which still remain. This has no effect whatever upon the form of the sinuosities of the curve; it merely serves to prevent it from dwindling away in its earlier portions, and to prevent the dropping of trees from causing apparent sinuosities where none exist. From 1883 back to 1850 the curve is based on 74 trees. Then group II is dropped, and the curve is based on 25 trees from 1849 to 1812. Finally, 14 of the trees of group III are dropped, leaving only 9 which carry it back to 1766. The earlier portions of this curve do not appear in figure 44, but are used in later discussions.

In figure 44 a certain degree of agreement can be seen between the curve of growth and the curve of precipitation. This becomes clearer when the simple rainfall curve is replaced by the smoothed curve shown in the middle line. This smoothed curve is made by taking the mean of three years' rain and plotting it in the third year of each group of three. The reason for plotting it in the third year instead of the middle year is that the effect of a rainy season can not possibly be felt before it occurs, but is felt in the years succeeding its occurrence. Between the smoothed curve of precipitation and the curve of growth a considerable degree of agreement is manifest. For instance, the rainfall maxima of 1862, 1868, 1876, 1886, 1895–97, 1901, and 1907 are all accompanied or closely followed by arboreal maxima. Marked disagreement, however, is evident in such years as 1878, 1882, and 1904. The explanation of these discrepancies seems to be found largely in the seasonal distribution of the precipitation, as is shown in figure 45. For example, the smoothed rainfall curve rises irregularly from 1871 to 1880, and judging from the 10 years before this period and the 20 or more years following it, we should expect the tree curve to do likewise. Up to 1877 the two do agree very well, but then comes a marked discrepancy lasting till 1882. Figure 45 suggests the probable cause of this. It shows the average seasonal distribution of precipitation since 1850 at San Francisco in the dotted line, while the other lines show the distribution for special years, either there or at Fresno. The year 1876–77 was one of the worst on record. Not only was the rainfall scanty, but its distribution was perhaps the worst since records have been kept. October was rainy, but precipitation in that month is of little use, since it either takes the form of rain, or else having fallen as snow it melts off unless promptly covered by fresh supplies. No new snow came in either November or December. January had a good supply, although not quite the average amount, and each of the next four months received only a third of the normal supply. In May the ground must have been as dry as it usually is in August. The growth of vegetation must have been checked almost as soon as it began, and the trees must have suffered sadly. Apparently they were so injured that they could not make a good growth the next year in spite of abundant precipitation, well distributed; then they began to recover, and by 1882 were in such a condition that they grew well in spite of scanty precipitation. That year, however, was very different from 1877. The fall and early winter were dry, but February, March, and April equaled or exceeded the normal, and those are apparently the most important months. In 1904 a similar case occurs: The precipitation remains at a low point, but the growth of the trees is accelerated. The cause seems to be plainly evident in the unusually large fall of snow or rain during February, March, and April, as shown in figure 45. Thus we might go on to analyze year after year,

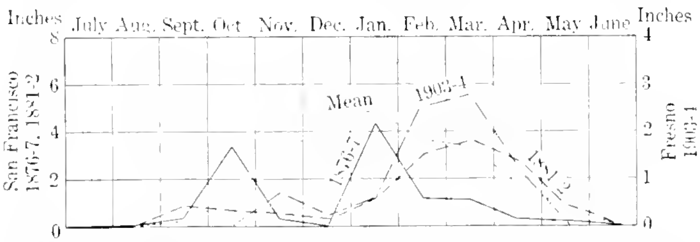


FIG. 45.—Mean Monthly Distribution of Rainfall Compared with Distribution in Exceptional Years. San Francisco–Fresno.

and find causes for a large number of the divergencies between the curves of growth and precipitation.

The seasonal distribution of rainfall, however, is only one of the two chief factors which cause the curve of the trees to disagree with that of the rain. The other is what Professor Douglass has called the conversation factor. The extent to which the curve of growth lags behind that of precipitation, even when the 3-year mean rainfall is plotted in the last of the 3 years of any given group, suggests that this factor plays a more important part here than among the pines in Arizona. It apparently depends not only upon the amount of water stored in the soil, but upon the amount of reserve strength which the plant has been able to acquire by enlarging its root system or by the growth of branches and buds.

Figure 46 represents the result of the most satisfactory of five or six methods by which an attempt has been made to gage the effect of the rainfall of preceding years upon the growth of the sequoias at Hume during any particular year. From the 63 years for which records of rainfall at San Francisco and Fresno are available (that is, from 1849-50 to 1911-12) I have selected two groups. One group consists of 15 years, during which the trees at Hume not only formed rings having more than the average thickness of 3.5 mm. according to the corrected figures used in plotting the curve, but also grew faster than during the preceding year by an amount of 0.25 mm. or more. The other group consists of 14 years, during which the trees not only grew less than the average amount, but also grew less rapidly than during the preceding years by an amount of 0.23 mm. or more. This last figure was selected instead of 0.25 mm. simply in order to make the two groups as nearly equal as possible. In the selection of these two groups it is clear that two chief criteria are employed, the absolute amount of growth and the relative amount. A glance at the curve of growth in figure 44, the upper solid line, will show how the two criteria are applied. According to the first criterion (absolute growth) the years are divided into two classes. One class comprises all those which grew more than 3.5 mm. and whose position in the diagram is above the median horizontal line, while the other class comprises all which grew less than 3.5 mm. and whose position is below the line. From the class of rapidly growing trees a smaller class was selected by means of the second criterion, relative growth. All the years in which the growth was more than 0.25 mm. in excess of the preceding year, or in other words all the years which are preceded by a rapidly rising portion of the curve in figure 44, were selected and the rest rejected. In the same way, among the slow-growing trees selection was made of all which show a growth of 0.23 mm. or more in deficiency of the preceding year—that is, which are preceded by a rapidly falling portion of the curve.

For these two groups of years of rapid and increasing growth on the one hand, and of slow, decreasing growth on the other hand, I have calculated the average rainfall, first during the season preceding the period of growth, then during the two seasons preceding it, and so on until 5 years have been included. The results appear in figure 46. In the figure the upper curve represents the rainfall of what we may call the progressive years, and the lower of the reactionary, while the solid horizontal line indicates the mean rainfall for the entire period of 62 years, which amounts to 10.67 inches for Fresno. The meaning of the curves is plain. During the years immediately preceding times of rapid and increasing growth the average rainfall was 12.58 inches; for the period of 2 years preceding such times it was 12.02 inches; for 3 years 11.86 inches; for 4 years 11.30 inches; and for 5 years 11.17 inches, a series of figures which increases steadily as the times of rapid growth are approached. In the case of the slow-growing trees, on the contrary, the figures are for 1 year 9.98 inches, 2 years 9.51, 3 years 9.64, 4 years 10.08, and 5 years 10.53, a series which, in general, *decreases* as the times of slow growth are approached. If the two curves were carried back a few years farther they would coalesce. Figure 47 illustrates the same thing as 46, except that the mean rainfall for the first, second, third, fourth, and fifth years preceding the years of growth has been plotted instead of the means for periods of 1, 2, 3, 4, and 5 years. In either case it is obvious that the most favorable growth comes at the end of a series of 4 or 5 years of increasing rainfall, while the slowest growth follows a similar series of years of diminishing rainfall. In the case of slow growth we see evidence that a slight improvement in the amount of rainfall is not able to overcome the harmful effects of a preceding series of bad years. Otherwise the curve of the slow years would not hook up at the right-hand end, showing that after a series of bad years, even though the rainfall increases somewhat, the trees do not respond at once.

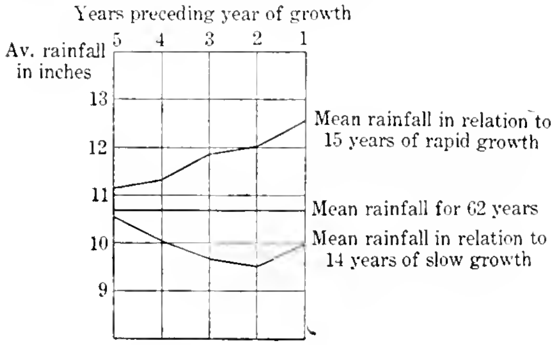


Fig. 46.—Conservation Factor in the Relation of Growth and Rainfall, Method I.

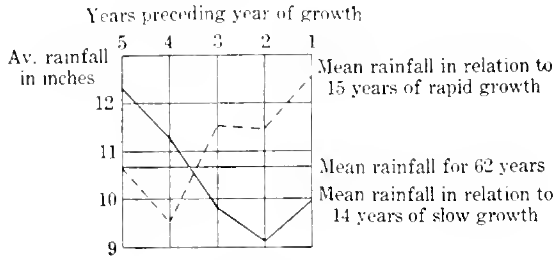


Fig. 47.—Conservation Factor in the Relation of Growth and Rainfall, Method II.

If we are right as to the relation of the rainfall of past years to the growth of the sequoia during any particular season, it ought to be possible to reduce this relation to a formula, just as in the case of the yellow pines of Arizona. Professor Douglass has kindly consented to work out the formula. It is given below, together with his comments:

"A trial of the 'accumulated moisture' formula of the yellow pines in Arizona shows that it does not apply to the sequoias of California, presumably because the precipitation is heavier among the Sierras than in the plateaus of Arizona. An 'additive' formula, on the other hand, gives an encouraging result, as is shown in the accompanying diagram (figure 48). This formula allows for strong conservation by the soil, not of the static type, as in a pond, but of the moving type as if a belated supply from the snows came to hand and then passed on. The tree, then, has moisture from the current year and from the first and second preceding years; and whichever of the three is greater, that one has the more effect. The formula is

$$T_n = K \cdot \frac{R_n^2 + R_{n-1}^2 + R_{n-2}^2}{R_n + R_{n-1} + R_{n-2}}$$

This is of course empirical and will be improved. It is worthy of study as illustrating what appears to be a difference in type of formula for different climates. Without doubt the reversal of this formula to ascertain rainfall from tree growth is much more difficult than that of the Arizona formula, for the tree automatically smooths the rainfall variations, but variations of a longer period than three years will be evident."

The gist of the relation of the growth of the sequoias to precipitation may be stated in a few words. In the regions whence our measurements have been obtained the growth depends primarily upon the amount of rainfall, but almost equally upon its monthly distribution. Owing to the conservation factor the rainfall of any single year is only one of the factors which determine the amount of growth. Only by taking a period of 3 or more years can we form an accurate judgment as to the actual amount of growth which corresponds to a given rainfall. Where a longer period than 5 years is concerned we may say with confidence that, if due allowance is made for age, longevity, and other factors, the thickness of the rings of growth is dependent upon the amount and season of the rainfall. Excessive precipitation may, perhaps, in some cases check growth, but as yet no evidence of this has been noticed, even in years where the precipitation amounts to two or three times the average. In the past, it seems safe to say, the relation of precipitation and growth must have been essentially the same as at present. Therefore we seem warranted in concluding that in our long curve of growth, extending back 3,000 years, and given in figures 38 and 50, high places indicate abundant moisture and low places indicate drought. How greatly the rainfall of the past exceeded that of the present we can not yet ascertain

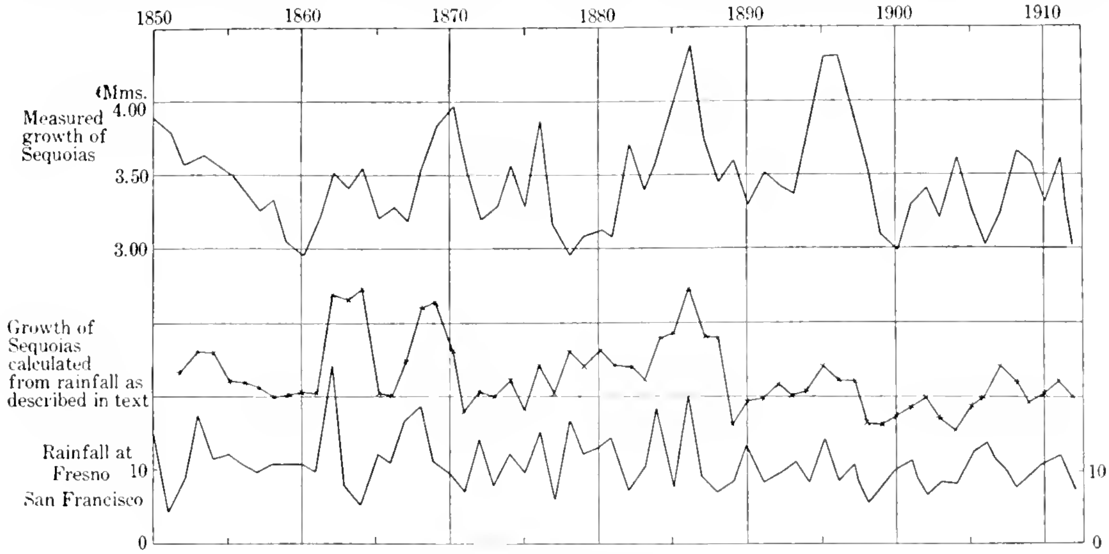


FIG. 48.—Tree Growth in California Calculated from Rainfall, by A. E. Douglass. (See Table I, pp. 328–329.)

positively. In the modern sequoias the growth during the group of 15 favorable years exceeded that during the 14 unfavorable years by 0.43 mm., or 12.3 per cent of the mean. The rainfall during the periods of 5 years preceding the favorable years exceeded that during the similar periods preceding the unfavorable years by 0.64 inch, or 6 per cent of the mean, while if a 4-year period is taken instead of 5 the excess is 1.22 inches, or 14.3 per cent. From this it would appear that the thickness of the rings of growth is closely proportional to the rainfall. By this I do not mean to be understood as making any exact or positive statement, but merely as indicating the order of magnitude of the relative changes of rainfall and growth. Increasing the rainfall by 10 per cent might increase the thickness of the rings by 5 per cent or 20 per cent, but it is quite certain that it would not increase the thickness by 50 per cent, nor would its effect be so small as 1 per cent.

Before attempting an analysis of the changes of climate indicated by the long curve of the sequoia, let us attempt to gain some light on the nature of the monthly distribution of the rainfall and the seasonal variations in storminess during favorable as compared with unfavorable years. Because of the projection of the effects of past years into those that follow, that is, because of the conservation factor, it is not easy to ascertain exactly how much influence is to be attributed to the seasonal distribution of the rain of a single year. Yet we have seen that this is a highly important factor. If the precipitation all came in the form of rain in the fall, or if it all fell as snow after the ground was frozen and then was rapidly melted by heavy rains in the early spring, the effect upon trees would be quite different from that which would result from a uniform distribution throughout the fall, winter, and spring, or from heavy precipitation from February to May.

Four ways of testing the matter suggest themselves: (*A*) First we may pay attention only to the amount of moisture and may compare years of exceptionally heavy and exceptionally light precipitation. (*B*) Next we may pay attention only to the growth of the trees and may compare the years of rapid growth with those of slow growth, using the two groups that we have already employed in our study of the conservation factor. (*C*) Again we may combine growth and rainfall, and compare two groups of years, in one of which both the rate of growth and the rainfall increase in amount, and in the other of which both quantities decrease. (*D*) And finally we may combine growth and rainfall in still another way, forming two groups of years in one of which both the rainfall and the rate of growth are above the normal and in the other of which both are below the normal.

TABLE 7.—*Groups of favorable and unfavorable years in California.*

Years	A		B		C		D		E	
	Favorable.	Unfavorable.	Favorable.	Unfavorable	Favorable.	Unfavorable.	Favorable.	Unfavorable	Favorable	Unfavorable.
1849–50	×						×		×	
1850–1		0				0				0
1851–2										
1852–3	×				×		×		×	
1853–4										
1854–5										
1855–6						0		0		0
1856–7						0		0		0
1857–8					×			0		
1858–9				0				0		0
1859–60								0		
1860–1								0		
1861–2	×		×		×		×		×	
1862–3		0				0		0		0
1863–4		0								
1864–5				0						
1865–6										
1866–7	×									
1867–8					×		×		×	
1868–9			×							
1869–70										
1870–1		0		0		0		0		0
1871–2	×			0						
1872–3		0						0		0
1873–4			×				×		×	
1874–5				0		0				
1875–6	×		×		×		×		×	
1876–7		0		0		0		0		0
1877–8	×									
1878–9										
1879–80	×				×				×	
1880–1	×					0				
1881–2		0	×							
1882–3	×			0				0		0
1883–4			×		×		×			
1884–5		0	×						×	
1885–6	×		×		×		×		×	
1886–7						0				
1887–8		0		0		0		0		0
1888–9		0			×					
1889–90	×			0						
1890–1			×							
1891–2								0		
1892–3						0				
1893–4			×							
1894–5			×		×		×		×	
1895–6										
1896–7										
1897–8		0				0				0
1898–9		0		0				0		0
1899–1900										
1900–1					×			0		
1901–2		0						0		0
1902–3								0		
1903–4			×							
1904–5	×			0						
1905–6	×			0						
1906–7		0								
1907–8			×							
1908–9										
Total years	16	14	14	12	11	12	9	17	10	13

In each of these four cases we have a group of favorable years to be compared with a group of unfavorable. The comparison can most easily be made by means of a series of diagrams showing the average amount of rain for each month in each group of years. This is done in figure 49, where the solid lines represent the favorable years, the dash lines the unfavorable, and the intermediate dotted lines the mean for all years. The dates and figures on which the curves are based are given in tables 7 and 8. From table 7 it appears that 29 years are included in one or another of the favorable groups; 18 of these are included in only one favorable group, 3 are in two groups, 2 are in three groups, and 6 are in four. The unfavorable groups include 35 years, 20 of which are included in only one group, 9 in two, 2 in three, and 4 in four. Only 10 years fail to fall in any group, while 12 fall in both a favorable and an unfavorable group. One of these last, 1874–75, falls in one favorable group and two unfavorable. Omitting all years which fall in only one group, or in both favorable and unfavorable groups, there remain 11 which fall in two or more favorable groups and 14 which fall in two or more unfavorable groups. These 25 years form two final groups (E in the tables) representing the extremes of the two conditions with which we have to deal. The average monthly distribution of rainfall in them has been plotted as the last of the sets of curves in figure 49, and may be regarded as the most typical.

TABLE 8.—*Mean monthly rainfall (in inches) of the groups of favorable and unfavorable years shown in table 7.*

		July.	Aug.	Sept	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May.	June.
A.	Favorable	0.00	0.00	0.17	0.67	1.98	3.48	3.13	2.28	1.89	1.33	0.52	0.11
	Unfavorable	0.00	0.00	0.22	0.41	0.55	1.13	1.02	0.94	1.11	0.61	0.27	0.05
B.	Favorable	0.00	0.00	0.18	0.30	1.39	2.42	2.95	2.02	1.69	1.15	0.35	0.19
	Unfavorable	0.00	0.02	0.35	0.99	1.02	1.92	1.79	1.14	1.58	0.13	0.72	0.10
C.	Favorable	0.00	0.00	0.09	0.39	2.45	2.55	3.35	1.73	1.87	1.54	0.37	0.16
	Unfavorable	0.00	0.00	0.07	0.46	0.62	1.56	1.88	1.45	1.04	0.68	0.22	0.08
D.	Favorable	0.00	0.00	0.09	0.46	2.67	3.56	4.16	2.00	2.17	1.39	0.33	0.16
	Unfavorable	0.01	0.01	0.20	0.40	1.08	1.50	1.19	1.36	1.49	0.59	0.15	0.05
E.	Favorable	0.00	0.01	0.08	0.15	2.59	3.39	3.85	1.87	2.05	1.71	0.35	0.15
	Unfavorable	0.00	0.01	0.25	0.53	0.57	1.33	1.46	1.77	1.35	0.52	0.10	0.06

A comparison of the curves of figure 49 is interesting. In group A, 16 years with 12 inches of rain are compared with 14 having less than 8 inches. Both curves are here quite regular, and in general form resemble the mean curve for the entire 60 years since records have been kept. In all three precipitation increases from July to December, and decreases from January to June, the only marked exception being February in the curve for years of low rainfall. The work of Professor Kullmer, as explained later, shows that during the favorable years of this group the storminess of the United States as a whole slightly exceeded the average, while during the unfavorable years it was distinctly less. The next set of curves indicates the distribution of precipitation during 14 years of uncommonly favorable growth and 12 years of uncommonly unfavorable growth, no attention being paid to the amount of rainfall. The position of the curve for the favorable years above that for unfavorable years from November to April, inclusive, indicates that the growth of the trees is strongly influenced by the amount of rain during the preceding winter. But the fact that these two curves are much closer to one another than are the two representing groups of years selected solely upon the basis of rainfall emphasizes the conclusion already reached that the amount of growth depends upon the rainfall of a considerable number of past years, not upon that of one year alone. The next two sets of curves represent 12 favorable and 12 unfavorable years selected because of the criteria mentioned under C, and 9 favorable and 17 unfavorable years of the type D. Inasmuch as both of these sets are based on the relation of rainfall and growth rather than upon either one alone, they give a truer impression than do the preceding sets. Finally, the curves of the last set, E, representing 10 favorable and 13 unfavorable years, which combine special conditions of both rainfall and growth in the highest degree, deserve careful consideration. They present the same general appearance as the other two sets of curves which combine our two factors, but in a higher or more intensified degree. During the four months from July to October, inclusive, all three curves, favorable, mean, and unfavorable, practically coincide; then in November the favorable curve jumps to a great height, indicating an abundant fall of snow at the beginning of winter, while the unfavorable curve remains horizontal, indicating an open season with only a few inches of snow. Throughout December and January the favorable curve remains far above the unfavorable, in February the two almost coalesce, while in March and April the favorable curve is somewhat higher than the other, although by no means so much so as during the first part of the winter. Early snows aid the growth of trees by keeping the ground almost unfrozen and thus allowing the melting snow to sink in and thoroughly saturate the soil. In addition to this the absence of frost in the ground permits the trees to begin growing almost as soon as the snow disappears, and thus the growing season is lengthened, a matter which is of especial importance in a region like the Sierras, where the drought is extreme. The effect of late snows, or spring rains, on the other hand, is more direct and hence still more important.

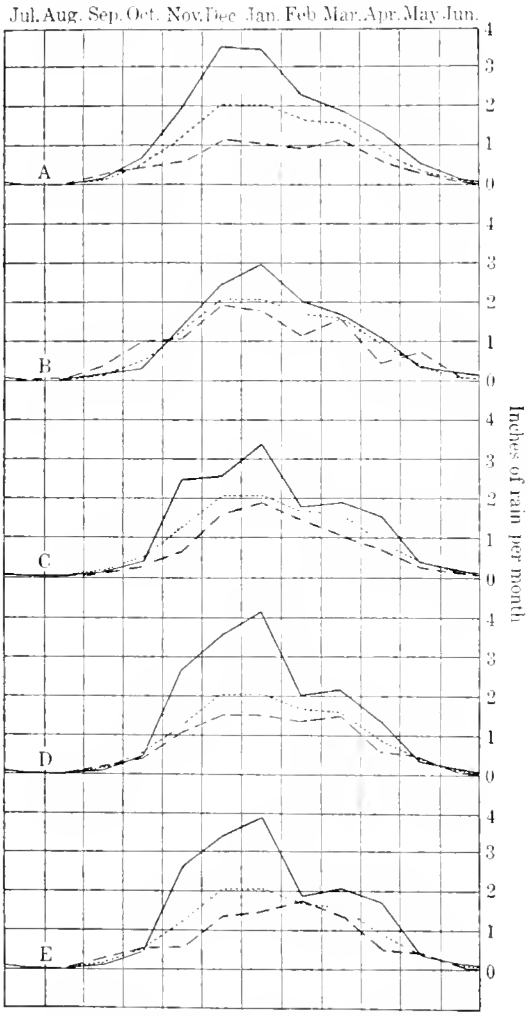


Fig. 49.—Rainfall by Months in Favorable and Unfavorable Years.

Mean of all Years = ...
Unfavorable Years = ----
Favorable Years = ——

The climatic conditions indicated by the curves of figure 49 can be interpreted in terms of cyclonic storms. Part of the precipitation of the Sierras is derived from cyclonic storms. The growth of the trees appears to be especially promoted in years when the storms begin early and continue late. Although the subject has not yet been well investigated, it appears that during such winters the storms move farther south than usual. Possibly an indirect indication of this is found in the rapid decrease of precipitation during February. In winters of the type characteristic of northern regions the storms begin early in the season and there is a rapid increase in the amount of precipitation; then, as winter conditions come to prevail completely and the continent becomes thoroughly chilled, a great continental area of high pressure and low temperature is developed. This prevents storms in the area where it prevails and gives rise to calm, clear weather, bitter cold perhaps, but sunny and free from wind. The storms meanwhile are pushed to the edges of the area of high pressure—that is, toward the oceans and the south. Then, when spring approaches and the high-pressure area is broken up, storms once more prevail, but not with such severity as during the first part of the winter, for they are soon affected by the coming on of the conditions which prevail in summer when the winds are weaker than in winter. When winters of this type prevail in California, the ordinary California type is pushed farther south. At such times regions like southern Arizona would probably get as many storms as Utah now gets, while places as remote as the Gulf of Mexico would be visited by frequent "northers."

Meanwhile our general conclusion may be summed up thus: Judging from what we have seen of the rainfall of to-day and of its relation to the growth of the sequoias, high portions of their curve seem to indicate periods when the winters were longer than now, when storms began earlier in the fall and lasted later into the spring, and when mid-winter was characterized by the great development of a cold, continental, high-pressure area, which pushed the storms of the zone of prevailing westerly winds far down into subtropical regions and thus caused subtropical conditions to invade what is now the zone of equatorial rains.

With this interpretation of the curve of the sequoias before us, we are prepared to consider its meaning in reference to the history of the world as a whole. Figure 50 shows a dotted line representing the approximate climatic fluctuations of historic times as given diagrammatically on pages 327 and 403 of "Palestine and its Transformation." Leaving out of account the slope of the sequoia curve to correspond with the changes in level of the Caspian Sea, let us see to what extent these two entirely independent curves of tree growth in California and of climatic pulsations in Asia agree. The number of maxima in the Asiatic curve is far less than in the one from California, but this is of no special significance. By its very nature the Asiatic curve is a mere approximation and can not be expected to show minute details. The evidence on which it is based, especially in the early portions, is so scanty that long gaps, sometimes 100 or 200 years in length, may intervene between two points for which data are available. In such cases the method adopted was to draw a straight line between the points regardless of the fact that fluctuations of much importance may have taken place in the interval. Moreover, even though the Asiatic lines of evidence point to exceptional aridity or moisture, we can not in most cases be sure that they indicate the dates when those conditions reached a maximum. For example, we find evidence of aridity both before and after 1200 A. D., while moist conditions are indicated in 1000 A. D. and 1325 A. D., but we can not be sure that these are exactly the times of the true maxima and minima of rainfall, nor can we be certain as to whether the dry periods or the moist periods were more prolonged. Hence it is a pure matter of personal judgment whether we shall draw a U-shaped or a V-shaped curve. In addition to all this it has thus far been generally impossible to determine how low a given depression should fall. For example, at 300 A. D., 650 A. D., and 1200 A. D. evidences of increasing aridity are especially noticeable; hence the curve drops deeply. Yet so far as the actual facts are concerned the lines might have been drawn as indicated by the dashes. Finally, although the writer was not at the time conscious of it, the exact form of the Asiatic curve was determined in some respects by a preconceived idea which now appears to be erroneous. The idea was that changes of climate must be gradual and that lines with sharp angles and sudden risings or fallings could not possibly represent the facts. This, for example, prevented the maximum in the sixth century from being placed as late as certain ruins would suggest. Inasmuch as everything pointed to extreme aridity about 625 A. D., it was supposed that the change toward that aridity must have begun at least half a century or more prior to that time; it was not realized that a moderate change might occur suddenly when conditions were already none too favorable, and might produce the same results as a greater change acting less rapidly. Taking the Asiatic curve as a whole, then, we must bear in mind that it is only a preliminary sketch, a pioneer attempt to elucidate a most complex subject, and that the necessity for visualizing our conclusions in the form of a curve compelled the making of a large number of more or less important assumptions.

Bearing in mind, then, the limitations of the Asiatic curve, let us compare it with the main features of its fellow from California. At the beginning the two curves take a sudden drop in close harmony, a rather remarkable coincidence, but one that must not be much emphasized, since the California curve is based on a single tree and the Asiatic curve on the evidence of a few famines and an uncommon degree of movement among the peoples of the lands around the eastern Mediterranean. Next we get pronounced disagreement,

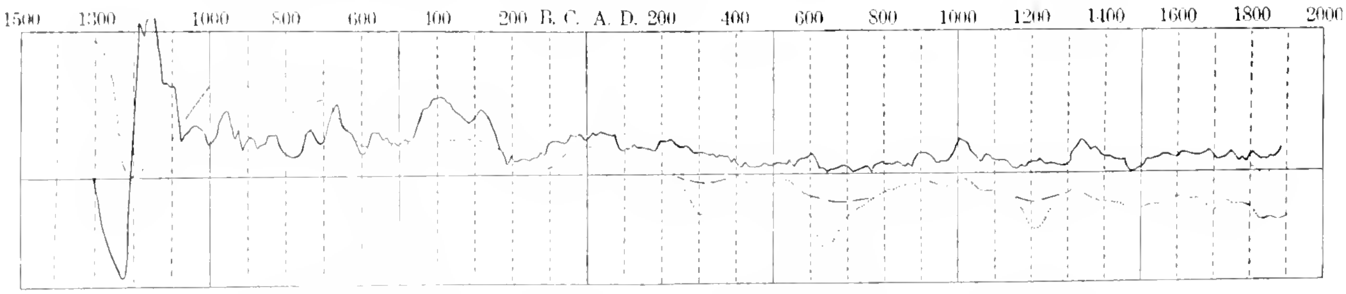


FIG. 50.—Changes of Climate in California (——) and western Asia (......) during Historic Times.

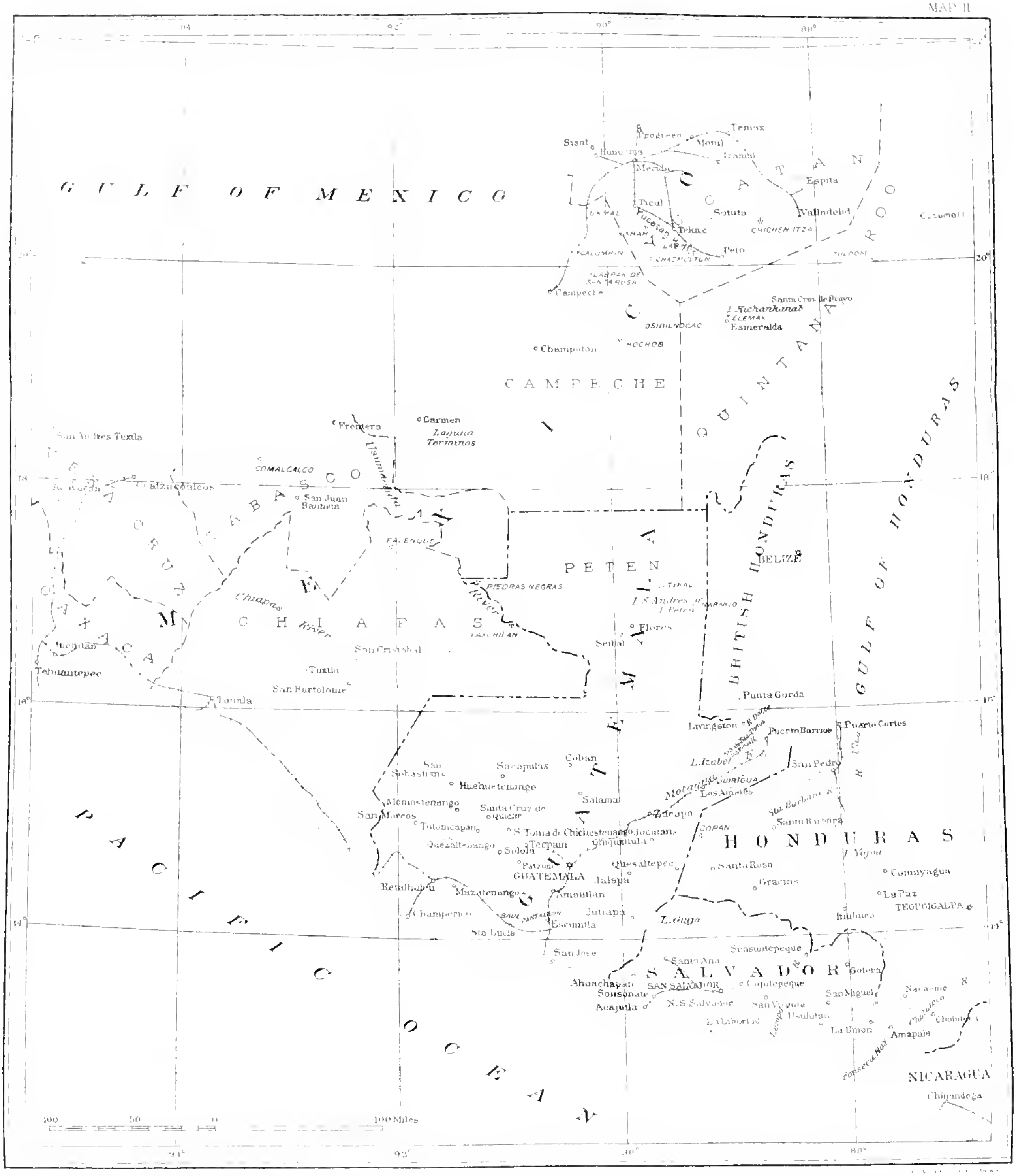
but this is less significant than the pervious agreement. It may be due simply to absence of data in compiling the Asiatic curve. Between 1200 and 950 B. C. no climatic data whatever had come to light in Asia when the curve was drawn; hence these two points were connected by a straight line. If our information had been fuller we might have been led to draw a curve similar to that of the sequoias, although less exaggerated. At 950 B. C. both curves show a decided maximum. Then for 250 or 275 years they swing downward and again upward, smoothly in one case and with many minor variations in the other, and reach maxima at 690 and 660 B. C., respectively. Considering the fact that the tree curve is much exaggerated because this portion is founded on so few trees, while the other curve is based on very scanty historical data, the agreement may be considered close. Next, both curves drop to a minimum in 600 B. C., after which the trees rise to a marked maximum in 400 B. C., while the Asiatic curve rises only a little and has no corresponding maximum. Here, once more, we have a distinct disagreement. It is more significant than that of the twelfth century B. C. because it comes later when the number of trees is larger and historical records more numerous than six centuries before, but it is of the same general type. In the period from 600 B. C. to 300 B. C. the Asiatic curve is drawn as a straight line because of the absence of any positive data during that long interval. If further information were at hand the Asiatic curve would undoubtedly be sinuous, and the few scraps of evidence available indicate that it quite certainly would not be low at 400 B. C. and probably would be high. The next maximum comes at 300 B. C. in one curve and 280 in the other, a good agreement. The succeeding minima culminate nearly 100 years apart, but here again the basis of the Asiatic curve is merely evidence of heavy precipitation about 300 B. C. and of low precipitation 150 years later. There is nothing to show how far the curve should depart from a straight line or the exact point where it should be at a minimum. Here, then, as in the twelfth century B. C. and at 400 B. C. the two curves disagree, but the disagreement is of a purely negative character and hence of no great significance. For the next 380 years, from about 130 B. C. to 250 A. D., the curves agree to a remarkable extent. Then comes a disagreement, the first which is genuinely positive and hence significant. The pronounced Asiatic minimum at 300 A. D. indicates one of two things. Either the climate of Asia at that time suffered a change which did not affect California, or else a distinct mistake has been made in the Asiatic curve. In view of the close agreement of other portions of the curve I am inclined to the second supposition. The fact that indications of aridity happened to be especially well preserved at the time has probably caused me to carry the Asiatic curve lower than is justifiable. It is possible that there really was a disagreement between Asia and America, but it is more probable that the concentration of evidences of aridity in the way of abandoned ruins and the like at that particular period led me to infer a pronounced minimum at a date when there was merely a greater degree of aridity than hitherto, although not so great a degree as ensued within a century or two. In general, as has already been said, the three noticeable depressions in the Asiatic curve, namely, those in 300, 650, and 1200 A. D., are probably exaggerated, because special events, due apparently to increasing aridity, happened to culminate at about those dates. Yet each of the three comes at a time of increasing aridity in the sequoia curve, and in the case of the minima of 650 and 1200 A. D. the sequoia curve is also close to its lowest point.

Returning now to our minute survey of the curves, the maximum at 400 A. D. in the Asiatic curve is wholly out of harmony with the California curve as it now stands. If, however, the minimum of 300 A. D. is a mistake, the succeeding maximum becomes merely a place where the descent of the curve is checked, just as in the tree curve. From 400 to 550 A. D. the curves agree. The maxima of 550 in Asia and 610 in California are probably identical, although for reasons already explained the Asiatic curve drops too soon. In the next section, from 600 A. D. to 1500 A. D., if allowance is made for the exaggeration of the Asiatic minima, the two curves agree closely for 900 years. Here, as at the time of Christ, the agreement is such that it can scarcely be a matter of chance. After 1500 the small fluctuations agree to about the same degree as do the large ones for the preceding 2,000 years. The general trend of the American curve is upward, however, and that of the Asiatic slightly downward. In this case the Asiatic curve is probably correct, for it is based largely on recorded levels of the Caspian Sea. The American curve, on the other hand, is probably wrong. This is the portion which is most seriously subject to errors due to the flaring of the sequoias at the base of the trunk. A slight correction has been applied for this, as already stated, but from the scarcity of young trees and from the general agreement of California with other regions, it seems as if this correction should have been greater. Probably the curve during the nineteenth century should be in the position indicated by the fine dotted line in figures 50 and 54.

The conclusions to be drawn from our two independent methods of investigating the climate of the past may now be summed up. Three points stand out with especial clearness. First and clearest, important climatic pulsations have apparently been in progress throughout the historical period. They have a length of centuries, but do not show any regular periodicity. They are often characterized by sudden changes of considerable magnitude. The agreement of all our lines of evidence appears to establish the reality of the pulsations upon so firm a basis that there seems little likelihood that future work will put it in question. Doubtless the details of our curves will be altered, but their sinuous character with its indications of climatic pulsations is not likely to be destroyed.

In the second place, climatic pulsations in western America and in similar latitudes in western and central Asia are probably synchronous and of the same type. This conclusion is by no means so firmly established as is the reality of the pulsations, but it possesses a high degree of probability. In the 3,200 years covered by our two curves only the 200 years from 250 to 400 A. D. and 550 to 600 A. D. show positive disagreements which, if confirmed, would militate against the conclusion just reached. During a much longer period, about 800 years all told, the two curves show negative disagreements, not due like the others to the direct interpretation or misinterpretation of actual facts, but to the mere absence of data. Finally, for 2,200 years the two curves are in essential harmony so far as their main fluctuations are concerned. Considering, then, the imperfections of the Asiatic curve and the fact that the respects wherein it disagrees with the American curve are those where it is known to be most liable to error, we may regard it as highly probable that the main climatic pulsations of the temperate portions of central and western Asia agree with those of the same latitude in western America. If these two regions, 10,000 miles apart, thus agree, it seems probable that in regions lying in the same latitude and having the same seasonal distribution of rainfall, similar changes must have taken place all around the globe, or at least over all the continents, while corresponding, although not necessarily similar, changes must have occurred in other latitudes. An apparent corollary of this conclusion is that these changes were due to a shifting of the world's climatic zones because of an alternate increase and decrease in the intensity of atmospheric movements, but this corollary has by no means the same degree of probability as the main conclusion whose verity it in no wise affects.

The third of our conclusions depends upon the verity of the first two. The agreement of the mathematically derived curve of the sequoias with the Asiatic curve based on totally different kinds of evidence seems to confirm the validity of the methods employed in dealing with those other kinds of evidence. This confirmation has important consequences. In all studies of the climate of the past it is far easier to see and interpret signs of the general prevalence of relatively moist conditions than to see and interpret the signs of climatic pulsations. On this rock, almost without exception, careful students of the subject have come to grief, for as soon as they have perceived evidences of a degree of aridity in remote historic times at all approaching that of to-day, they have jumped to the conclusion that such conditions have prevailed always, instead of only temporarily. If the methods which were first employed in Asia and Greece, and have now been applied to America, as set forth in the first part of this volume, are competent to accomplish the task of correctly dating the chief climatic pulsations, it seems as if they must be competent to accomplish the easier task of determining whether the climate of the past as a whole was different from that of the present. They point to this conclusion more strongly than to that of pulsatory changes. Hence we conclude not only that the climate of both America and Asia has been subject to pulsations, but that in general the average conditions of 2,000 or 3,000 years ago were moister than those of to-day. This is the reason for adjusting the general level of the earlier part of the sequoia curve by means of the variations in the level of the Caspian Sea, and for believing that the curve thus adjusted represents the approximate truth as to the climatic pulsations of temperate continental regions for the past 3,000 years.



SKETCH MAP OF A PART OF CENTRAL AMERICA
SHOWING LOCATION OF MAYA RUINS

CHAPTER XV.

THE PENINSULA OF YUCATAN.

MODERN GEOGRAPHICAL CONDITIONS.

Thus far our attention has been limited almost exclusively to the climatic zones north of the trade-wind belt. Only in one case have we made a slight excursion southward into the torrid zone in southern Mexico. There we found that evidences of climatic changes are as distinct and abundant as further north. Moreover, as will appear more fully below, their periodicity seems to be the same as that of the temperate zone, the first half of the fourteenth century having been a wet period not only in the basin of Mexico, but in California and in western Asia, while the end of the fifteenth century was dry. This Mexican region, however, is in many ways not truly typical of the torrid zone, since it lies on a high plateau from 5,000 to 7,000 feet above the sea and is cut off from the neighboring oceans by high mountains.

A true test of the torrid zone would demand the examination of some lowland region, and would be much more valuable if it included not only regions which, like the Mexican plateau, receive rain in summer only, but also places receiving it at all seasons. Moreover, such a place must contain ruins or other traces of human occupation in order to afford some indication of the dates of any possible changes. A region of precisely this kind is found in the low, triangular area which extends from latitude 14° to 22° in Central America. The base of the triangle extends about 500 miles in a direction east by south from the Isthmus of Tehuantepec along the Pacific Coast and across Guatemala to the center of Honduras, while the apex lies 500 miles north of the last point and is the northwestern promontory of Yucatan. The triangle is shown in the accompanying map. It includes the Mexican states of Tabasco and Chiapas, the entire peninsula of Yucatan, British Honduras, the two-thirds of Guatemala lying north of the Motagua River, and a considerable part of western Honduras. Here grew up the civilization of the Mayas, who possessed the highest culture attained by any American race before the coming of Columbus. Here are found some of the most remarkable ruins of any portion of the world. Part are located in the dry regions of northern Yucatan and part in the dense tropical forests where no civilized man now dwells. Something is known of their history, both from a few old records and from the ruins themselves. Hence here, more perhaps than anywhere else in America, we have an opportunity to test our climatic theories by the twofold criterion of a new climatic zone and a new type of civilization. The results are at first sight contradictory to those attained elsewhere, for the past appears to have been on the whole more arid instead of more moist than the present. More carefully interpreted, however, they are seen not to be contradictory and to afford not only a most interesting confirmation of the theory of changes of climate, but a valuable light upon the mechanism of such changes.

The best place in which to begin our main investigation into the Maya civilization and its relation to climate is the peninsula of Yucatan. In view of the importance of the subject, and inasmuch as Yucatan is a peculiar region and is imperfectly known to the majority of intelligent readers, I shall describe some of its more salient geographic features, and shall attempt to give an idea of their relation to the present habits and character of its Mestizo and Maya population. This is necessary because the most surprising feature of the country—that is, the great contrast between the past and the present—can only be understood on the basis of a knowledge not only of the wonderful ruins, but of the present state of civilization.

One of the first things that strikes the geographer when he faces the ancient greatness of Yucatan is the fact that the country is highly isolated, a condition which tends notably to retard rather than advance the growth of civilization. Toward the south and east the habitable portion of the peninsula is bounded by dense tropical forests which even in our day are penetrated neither by railroad nor road. The only way to traverse them is by means of Indian trails, winding and crooked, and often coming blindly to an end. Even these poor apologies for paths are impassable except with the help of a party of natives armed with big machetes for cutting the young trees and lianas which grow up with astounding rapidity. The inhabitants of the forests are limited to a few scattered bands of Indians in the lowest stages of civilization. Often the traveler may go for days without seeing a village or even a camp. On the other sides Yucatan is surrounded by water, but that does not make it accessible. The harbors on the east coast are said to be fairly good, but the country back of them is covered with the same kind of dense forest as the south, and hence they are almost useless as a means of getting at the important portions of the country. On the north the coast is bordered by an almost continuous line of sand bars and lagoons. Within the lagoons the water is quiet, and small boats can sail easily, but unfortunately it is not possible to go any great distance without meeting barriers which force the navigator to take to the open sea. There the waves raised by the prevailing trade winds, blowing freshly from the northeast, are so high as to make long voyages too dangerous to be commonly undertaken. So far as modern steamers are concerned conditions are no better. Like all newly uplifted coastal plains Yucatan is bordered by very shallow seas. The steamers of the Ward Line, the only one plying regularly to the country, are forced to anchor 3 miles or more from land and to send their freight and passengers ashore in a tug which pitches most disquietingly, even in comparatively good weather. In bad weather it is often impossible to make any landing whatever. On the west coast, known as Campeche, conditions are somewhat better because of less exposure to the winds, but the difficulties due to shallow water are not much different. Altogether the peninsula of Yucatan is a decidedly inaccessible region, and there seems to be nothing in its position to account for its past greatness. No great trade routes touch it, its near neighbors on every side are backward, and there seems to be little opportunity for the stimulation which comes by contact with people of other ideas and habits.

The form of the land in Yucatan is not any more favorable than is its location. As has already been implied, the northern part is a coastal plain newly uplifted from the sea. For scores of miles the general aspect of the country is absolutely flat. Near the center low hills rise to a height of 300 to 400 feet, and farther south the relief becomes greater. The most noticeable ridge, so far as the inhabited portions of the country are concerned, runs southwestward from a point about 30 miles inland from the northwestern corner of the peninsula. Its rounded hills are a prominent feature in the landscape as looked at from the plain to the east, but are nowhere difficult to cross; nevertheless they form a genuine barrier to civilization, largely because of their relation to water-supply, rainfall, and vegetation.

Practically all of Yucatan is composed of soluble limestone. This has given rise to one of the most widely known features of the country, that is, its underground drainage and "cenotes" or caves. The topography is almost universally of the unpropitious kind known as "karst." The karst, however, is not of the most common type, for in Yucatan we have to deal with a level plain instead of with a region of considerable relief. Because of the flatness and the porous nature of the soluble limestone such a thing as a river is absolutely unknown. Not even a brook is found in the whole country, and naturally there are no valleys. The only break in the flat monotony is afforded by innumerable little hillocks 5 to 15 feet high. They lie in no regular order, being merely the remnants which happen to have been left between depressions in which a little water gathers in the rainy season. The water stands in pools for a while, and by so doing tends to dissolve the hollows to a deeper level. Only rarely does the water of one hollow run over into another, and even then not in sufficient amounts to make real, running streams. Such being the case, the drainage of the country is confined to underground channels which exist in large numbers. Often the concealed waters dissolve large caves whose tops, in many cases, have fallen in, exposing the water at a depth of anywhere from 20 to 100 feet, and thus giving rise to the openings known as "cenotes." These broken-down caves are highly important to the inhabitants, for they are almost the only places where a permanent supply of water is naturally obtainable throughout the whole year. At the time of the coming of the Spaniards all the native inhabitants, the Maya Indians, as they are called, are said to have been clustered around them or else around the few "aguadas" or natural hollows which contain water during most of the year, although, unlike the cenotes, they sometimes dry up. Having no iron tools, the primitive Mayas were unable to dig wells, although to-day these can be dug almost everywhere with full assurance of striking an abundant and unfailing supply of water. The only difficulty is that in the hilly regions the wells have to be sunk to a depth of from 100 to 200 feet, and the labor involved is sufficient in many cases to prevent the inefficient people of the tropics from making the attempt. Where ground water lies at a depth of only 20 or 30 feet, as in most parts of the plain, wells are numerous. In many cases the water is raised by windmills, which seem to rise like a forest when one looks from a distance at such a town as Merida, the capital. During recent years, when Yucatan has grown rich from the henequen or sisal fiber industry, pumps run by gasoline or steam have in many places appeared.

Climatically, as well as in other ways, Yucatan is relatively simple. It lies in the trade-wind belt from 19 to 21 degrees north of the equator. In winter the brisk winds from the ocean pass over the land without giving up much moisture. The sky is clear a large part of the time, and although some rain falls in every month the amount in the northern parts of the country is insignificant. Farther south, however, or where the hills begin to rise, the rainfall increases rapidly, and showers are frequent. The temperature in winter is agreeable, being rarely extremely warm and never cold according to the ideas of people from the north. In spite of this there is considerable variety, especially when the so-called northers blow. These appear to be connected with the cyclonic storms of the United States. The wind blows violently from the north and reduces the temperature to the lowest points ever reached. The minimum, however, is rarely below 10° C. (50° F.), while the maximum, even in winter, is usually above 30° C. (86° F.), and may rise above 40° C. by the end of March. In summer, as might be expected in this latitude, the zone of equatorial rains exerts its accustomed influence and gives rise to heavy tropical showers. How greatly the summer rainfall exceeds that of winter may be seen from table 9, which gives the average monthly rainfall (in inches) for the 15 years from 1896 to 1910 inclusive at Merida.

TABLE 9.

Month.	Rainfall.	Month.	Rainfall.
January	0.88	July	4.90
February	0.68	August	8.48
March	0.58	September	4.46
April	0.74	October	3.04
May	1.70	November	1.94
June	5.61	December	1.36
		Total	34.37

The seasonal variation of rainfall is no more striking than its variation from region to region. In the north the rainfall is slight, being at a minimum on the coast in the neighborhood of Progreso. Here, in 1911, the only year for which statistics are at hand, the precipitation amounted to 13.5 inches. From 15 to 20 miles inland, at Merida, and at Motul and Temax which lie farther east, the precipitation for the same year was 35.7, 37.6, and 34.8 inches, respectively. Still farther inland, at places varying from 30 to 90 miles from the coast, the figures are as follows: Izamal, 40 miles due east of Merida, 49.2 inches; Espita, nearly as much again to the east, 48.7 inches; Tekax, 50 miles south-southeast of Merida, 53.3 inches; and Peto, about 30 miles southeast of Tekax but not so much among the hills, 47.7 inches. Finally, to the east and south of the places already mentioned we find an area of still larger rainfall, exemplified by Valladolid, which lies 100 miles east-southeast of Merida and about 50 miles from the Caribbean Sea. It had a rainfall of 66.8 inches in 1911. Southward beyond this point, to judge from the vegetation, the precipitation becomes still greater. The cause of the variation in rainfall is twofold. In the first place, the presence of hills in the south and southwest on the one hand, and the abundance of easterly oceanic winds on the east coast, give those regions much rain. In the second place, we are here near the edge of the area reached by the zone of subequatorial rains. Hence the amount of these rains increases rapidly toward the south.

With such marked changes in the amount of rainfall from place to place, it is evident that the vegetation must vary greatly, and that this fact in turn must profoundly affect the conditions of human life. The botanical works commonly emphasize the distinction between tropical bush, tropical jungle, and tropical forest. Nevertheless, in the mind of the average geographer, if I may judge from my own experience, and still more in the mind of the layman, the distinction often lacks sharpness. There is a still greater lack of appreciation of the significance of these three types in their effect on man. In Yucatan bush, forest, and jungle lie so close together that they can readily be compared. In the center of Yucatan lies a long narrow lake called Kichankanab, one of several which occupy hollows in the limestone of the southerly, more hilly portion of the peninsula. It is located about 100 miles east of Campeche, 100 west of the Caribbean Sea, and 100 south of the northern shore of the peninsula. If lines be drawn northeastward and northwestward from the lake to the corners of the peninsula they will include approximately the entire area of the Mexican administrative province of Yucatan, which comprises only about one-fifth of the whole peninsula. This small fifth of the country, together with a strip of the west coast reaching down toward Campeche, comprises the bush-covered portion, while the rest is covered with jungle or genuine forest. The western boundary of the bush area is nearly coincident with the small range of hills already mentioned as the most noticeable feature of the relief. The eastern boundary appears to be less distinct, although I have not seen it and can not speak with assurance. Where bush prevails the rainfall seems not to exceed 30 or 40 inches, while in the forested area it rises far higher. How great it is we do not know, for Valladolid with nearly 67 inches in 1911 is the only station whose figures are obtainable, and it lies on the relatively dry edge of the forest, not in its moist interior.

The distinction between bush, jungle, and forest is simple. Large trees demand that the soil in which they stand shall not be dry for any great length of time during the growing season. Inasmuch as the growing season may last the entire year in the tropics, large trees will not flourish in such a way as to form dense forests unless abundant rain falls at most seasons, although they may grow sporadically here and there. Smaller, more drought-resistant species, however, as well as bushes, are much less exacting in their demands for moisture. Some of them will grow almost anywhere provided that the ground is well moistened for 2 or 3 months during some portion of the year and there is sufficient warmth. In regions like Progreso, on the north coast, where the rainfall is only 10 to 15 inches, concentrated largely in the summer, the long dry period of winter prevents the growth of anything except small bushes 6 to 8 feet high; these, however, thrive in abundance, so that the country is well covered with vegetation and is everywhere bright green in summer.

In the dry winter, however, the leaves fall off and the landscape would be quite like that of a thick, bushy pasture in the United States at the same season, were it not that in the late winter and early spring some of the bushes bear brilliant red, yellow, or white flowers. As one goes inland from the north coast to regions of greater rainfall such as Tekax and Peto, bush begins to give place to jungle. The size of the shrubby growths increases; small trees, 20 feet high, become numerous; a considerable number of trees rise to a height of 30 or 40 feet, and some are much higher. In spite of this, however, neither the dense underbrush nor the larger trees suggest the deep, somber forest. Small growths not over 20 feet high and with stems only 3 or 4 inches in diameter predominate. Their aspect is like that of a second growth of timber in the northern United States, 15 or 20 years after the cutting of the original forest. A few bushes and even an occasional tree of some special species may remain green throughout the year, but during the dry season most become as bare as northern trees. With every mile that one advances into the interior, however, the jungle becomes more permanently green, the density of the lower growths increases, and the proportion of genuine trees becomes greater, until finally jungle gives place to genuine forest.

From the jungle to the forest the transition is rapid. A day's ride on horseback is often sufficient to take one from a well-developed sample of one to an almost equally well-developed sample of the other. The forest is of the kind whose descriptions we are so familiar with. Many of the trees remain green throughout the year. They rise to heights of 50 to 60 feet even on the borders of their province, and at the top form a canopy so that the ground is shady most of the time. Until 9 or 10 o'clock in the morning the rays of the sun, even in the drier part of the year when a portion of the leaves have fallen, scarcely reach the ground. Even at high noon the sunlight straggles through only in small patches. Long, sinuous lianas, often queerly braided, hang down from the trees; epiphytes and various other parasitic growths add their strange greens and reds to the continually varied complex of plants. Young palms grow up almost in a day, and block a trail which was passable only a few months before. Wherever the death of old trees forms an opening, a hundred seedlings begin a fierce race to reach the light and strangle their competitors. Everywhere the dominant note is intensely vigorous life, rapid growth, and quick decay, as befits the warm, moist air which rarely varies and never is so cold or dry as seriously to interfere with the development of plants, even of the most highly sensitive types.

Before passing on to discuss the effect of the vegetation and of other conditions on man, a word as to the relation of the karst phenomena to vegetation. It is sometimes stated that the paucity or rather the small size and xerophilous character of the vegetation ot northern Yucatan is largely due to the dryness of the soil occasioned by the draining away of the water through the caves and underground channels. Undoubtedly this is an important factor, but it may not be so important as is generally assumed. In no country where the growing season is at all warm can a rainfall of 10 to 15 inches produce anything except vegetation of a distinctly arid type. In a country so warm as Yucatan 30 or 40 inches is by no means a large rainfall, and even if none of it were lost in the karst, the country would still be relatively arid because of the great evaporation, especially during the long dry season. Still farther south not only on the edges, but actually within the limits of the genuine forest, karst phenomena seem to be as marked as near the northern coast, but this does not prevent the growth of the rankest kind of vegetation. It seems, therefore, that while the karsted character of the country plays a part in preventing the growth of vegetation, it is by no means so important as the relatively small amount of precipitation.

To turn now from the physical aspects of Yucatan to its people, the inhabitants consist of every gradation from pure Indians to pure Spaniards. The forests and the remoter villages are occupied by pure Indians of the Maya stock; the small towns and the less remote villages are peopled by a mixed race of Mestizos, in which the Indian element predominates, while in the larger towns and their environs the proportion of Spanish blood steadily rises. The degree of energy and initiative seems to vary in response to two factors, namely, the amount of Spanish blood and the length of time that a given stock has been in the country. As this point bears on our interpretation of the ruins a little amplification is needed. The pure Indian is a quiet, slow being, inoffensive and retiring unless abused. He seems never to work unless compelled. As for storing up anything for the future, the thought seems scarcely to enter his head. If he has enough to eat, he simply sits still and enjoys life until hunger again arouses him to activity. His wants are few and easily supplied. His agriculture begins by cutting the small growths of the bush, or jungle, girdling the larger trees, leaving the brush to dry during the season of little rain, and finally burning it off. Then he goes around with a pointed stick, making holes into which he drops corn, pumpkin seed, beans, and the seeds of one or two other vegetables. The corn is his chief reliance. When the crop is ripe, he has no thought of gathering it all at once and storing it away safely, perhaps in the form of flour or at least shelled. His method is to go out to the field in the early part of the dry season after the corn is well ripe, and half break each stalk in the middle so that it is bent over and the ears point downward. Little by little he picks what ears he needs for daily use, caring nothing that insects, birds, and beasts are also eating what they need. He knows that a quarter or a third of the ears may be spoiled, but so long as there are some for him, he cares little. The only thing that ultimately stirs him up to gather the remainder of the crop is the end of the dry season. Before the rains come he knows that he must harvest his crop and plant more seed or else he will starve. Therefore he arouses himself for the one period of effort during the year. He is hardly to be blamed for his apparent laziness. He certainly is lazy according to our standards, but he has little to stimulate him, and it is easy to get a living without much work. In good qualities, however, he is by no means lacking. He is extremely courteous, and according to all accounts he excels in both honesty and morality.

As the amount of Spanish blood in the people of Yucatan increases, their energy and resourcefulness increase. They also become more light-hearted and gay than the silent, sober Indians, but at the same time honesty and morality are said to decrease markedly. All classes of people, however, are decidedly slow compared with Americans or people of western Europe. In this connection a fact as to the Spaniards is worth recording. In Yucatan, as well as in other parts of Mexico, there is a surprisingly large number of recent Spanish immigrants. According to almost universal testimony these immigrants are better workers than the corresponding class of natives, no matter whether the natives are Indians, Mestizos, or Spaniards who have been in the country a generation or two. Something in the new environments seems to make people slow. In part it may be contact with an inferior race, but more probably it is a climatic matter. Doubtless the heat has much to do with it, but there seems ground for believing that the uniformity of the temperature is quite as harmful as its degree.

The distribution of the human inhabitants of Yucatan is very uneven. Practically all of the 400,000 who inhabit the peninsula live in the bush region, that is, Yucatan proper and the coastal strip north of Campeche. The rest of the country, comprising most of the province of Campeche and the federal district known as Quintana Roo, contains only a few wild Indians numbering 4,000 to 5,000. The reason is not far to seek; the tropical forest is too dense for them to conquer. This matter deserves emphasis, for it seems to be more important than is generally realized, and it may have a close bearing upon the problem of changes of climate. The descriptions of tropical forests are usually couched in such indefinite terms that it is hard to tell whether a given area in its pristine condition would be covered with jungle or forest. Practically all of the tropical regions, however, where the natives are at present in such a state of civilization that they live permanently in good-sized villages and depend primarily upon agriculture for a living, seem to be located where the prevalent natural growth is of the types which we have defined as bush and jungle. In such regions it is possible for a comparatively inefficient people to get a living by agriculture. The small trees or bushes with a diameter of 5 inches or less can readily be hacked down with almost any kind of heavy knife, while the larger ones can be girdled by cutting off the bark near the base, and will soon die. Provided this is done during the earlier part of the dry season, which is characteristic of all tropical regions where bush or jungle prevails, the bushes and perhaps some of the girdled trees will be dry enough to burn before the rains come again. Hence it is a comparatively simple matter to clear a tract and plant it. If some of the few larger trees of the jungle remain standing, little harm is done.

In the true forest the case is quite different. In the first place the trees are large, the majority having trunks at least a foot in diameter and many of them much more. Moreover, their wood is frequently hard. Hence it is difficult to cut them down. Only people of great energy are capable of doing so on any large scale. If the much easier process of girdling is resorted to, the trees will die in course of time, and it might seem as if even the inefficient people of the tropics could thus clear large areas. Unfortunately another difficulty arises, one which is serious where the trees are actually cut, and much more so where they are girdled. The climate of the true tropical forests is so uniformly moist that, even when trees have been felled, it takes a long time for them to become dry enough to burn. Moreover, while they are drying, new vegetation at once begins to sprout, and by the time the trees are ready to burn the new growth is so large that it prevents the fire from spreading from tree to tree. That this is so is evident from the fact that even in the jungle region the fires which are lighted every year in the spring to burn off the cornstalks rarely spread to any great distance in the uncut jungle. The speed with which plants grow in the tropics is far more than we commonly realize. One day on the southern edge of the jungle, near the forest but well out of it, my guide remarked that the land over which we were passing had been cultivated 3 years before. Already the bushes were 15 feet high. In the heart of the forest the growth is even faster. Hence the very rankness of the growth of vegetation is one of the primary reasons why man has never yet really mastered any considerable area where genuine tropical forests prevail.

Other reasons for this result also exist. Malarial fevers are much worse in the forest than in the jungle, and are worse in the jungle than in the bush. The natives are said to be immune to such fevers, but modern research throws considerable doubt on this. The adults are immune, but how about the children? The researches of Sir Ronald Ross and of the School of Tropical Medicine at Liverpool have shown that in countries badly infested with malaria adults do not suffer much from the disease, but that nearly half of the children have it year after year during childhood, and a large number bear its marks through life in the form of enlarged spleens and other injurious alterations of the organs. Every generation is apparently distinctly weakened by the diseases through which it passes in childhood. Similarly, in places such as Merida, where yellow fever is endemic, it is said that the natives never suffer and that epidemics break out only when newcomers arrive from outside. Many physicians now think, however, that large numbers of the children have the fever in infancy. Those who die are supposed to have suffered from other infant complaints, while those who recover are of course immune. In the case of yellow fever the after effects are generally not serious, but in the case of malarial fevers, especially such forms as prevail in the tropics, the debilitating results often last through life. Thus it may be that the severe fevers of the forests, attacking the children and killing many of them, leave the remainder permanently weakened and incapacitated for the work of forwarding civilization in their hard surroundings.

In general, so far as the effects of climate upon human efficiency are concerned, there seems to be a curious contradiction between equatorial and non-equatorial regions. In the equatorial regions a relative lack of rain seems to be beneficial, while elsewhere it is usually detrimental. At any rate the most progressive parts of the tropics appear in general to be comparatively dry, while the most progressive countries of the temperate zone are in general located in regions of comparative moisture, or else have been recently settled by people from regions of that sort. The dryness of the little strip of northern Yucatan where civilization now centers seems to be almost the only feature of the geographic environment which is distinctly favorable.

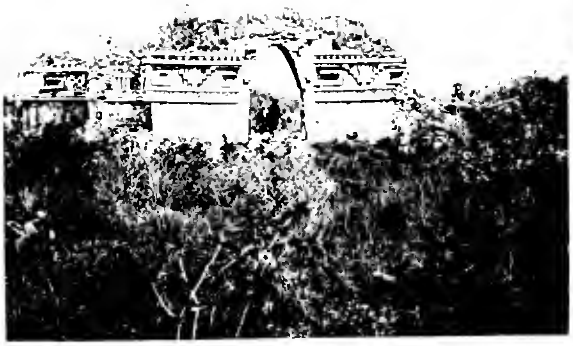
THE ANCIENT MAYA CIVILIZATION.

Among the noteworthy characteristics of Yucatan, we have seen that none is more interesting than the contrast between the civilization of the past and of the present. In spite of the slowness and inefficiency of the inhabitants as compared with the people of Europe, Yucatan compares favorably with other tropical lands, and enthusiastic travelers have sometimes claimed that Merida is the richest city in the world in proportion to its size. That the country has an uncommonly prosperous air is certainly true. This is partly due to the fact that the henequen or sisal fiber industry has proved most lucrative, especially during the period when the supply of Manila hemp, its chief rival, was cut off by the Spanish-American war. Without the sisal Yucatan would rank well among the countries of the torrid zone, but would by no means be so conspicuous as is now the case. The prosperity of to-day, however, is but a slight incident compared with that of the past. The present prosperity is in danger of being ephemeral. Much of it would vanish if another fiber as good as henequen should be discovered in places where it could be raised more cheaply than in Yucatan; and even if the prosperity should last, it is an extraneous matter. It is due to the demands of the United States and other countries, it is fostered by their steamship lines, and its benefits are chiefly reaped not by the Indians and Mestizos, but by people of Spanish blood, most of whom have not been in the country more than a generation or two. Moreover, its effect upon the country as a whole is slight outside of Merida. It has not stimulated the native population to any special activity, nor has it caused the construction of buildings whose ruins will endure to commemorate it. In Merida, to be sure, it has led to the erection of many stone buildings which will give to the archeologist of the future an idea of considerable prosperity, but there the matter ends. If the present inhabitants were to be suddenly removed and the country left desolate, the archeologist of 3000 A. D. would find few traces of the present civilization except small heaps of stones in the country districts, and the remnants of a number of mediocre buildings in the little provincial capital. There would be nothing to arouse his enthusiasm; the ruins of almost any county seat of 60,000 inhabitants in the United States or northwestern Europe would present far greater evidences of a high civilization. It would be almost obtrusively evident that Merida in its prime was merely a feeble imitation of a civilization whose real center was far away.

Turning now to the past, we find an entirely opposite state of affairs. The ruins of scores of superb temples and other structures scattered in the bush, jungle, and forest of all parts of Yucatan and the adjacent Maya lands proclaim unmistakably that the country once possessed a civilization which, for its period and continent, was the highest in existence. Here, not elsewhere, was the center, and here that civilization not only developed but persisted for century after century. The ruins, while not a tithe as beautiful as those of Athens, make upon the traveler the same impression of wonderful power and originality in their builders, the same sense of having been built by a people who were masters of their art and who gloried in their skill. Any detailed description of the ruins would be out of place in this volume, but a little discussion of them is needed in order to show how high the ancient civilization actually was and wherein lay some of its chief elements of greatness.

A


B


C


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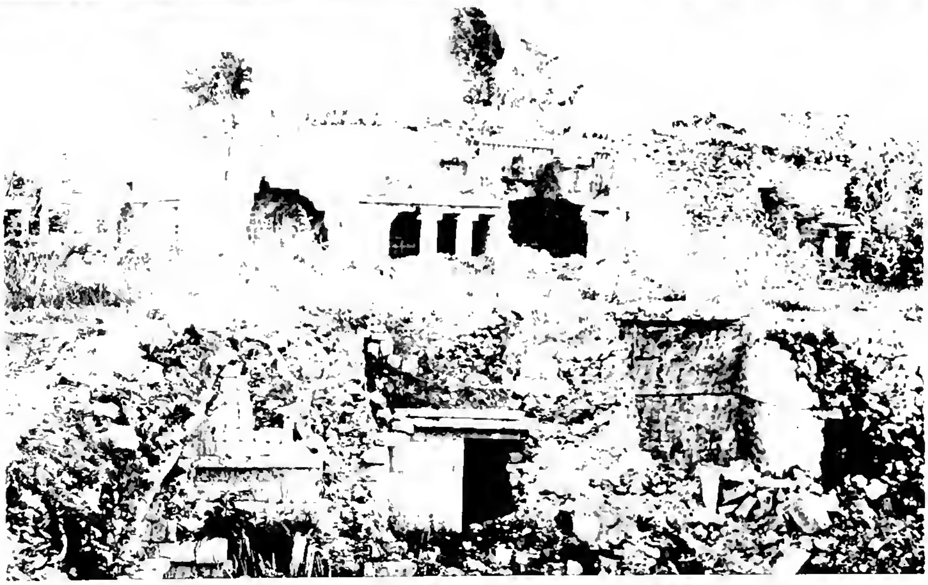


A. Market place in Yucatan, showing the best modern a[illegible]
B. Typical house in Yucatan.
C. Archway at Labna.
D. Farmer's hut in the midst of Labna, one of the greatest ancient [illegible] pumpkins [illegible] on field, corn stalks in foreground, and jungle of a few years [illegible]
E. Ruins of Chac-multun.

Unless these things are appreciated, we can not form a fair judgment as to why the past was so different from the present.

One of the most impressive features of the ruins is the abundance, size, and solidity of the various structures. For instance, at Chichen Itza, where within a radius of 25 miles on either side there are probably to-day not 5,000 people, there was once a vast city. Mr. E. H. Thompson, whose home has for years been directly among the ruins, says that the area of dense urban population was at least 6 miles square; that is, it comprised no less than 36 square miles, while beyond it lay abundant suburbs. Such a city, even if it had but two families to the acre, would have contained fully 230,000 people; whereas all Yucatan to-day has a population of only a little over 300,000. Chichen Itza, however, by no means stands alone. Ninety-two ruins are known, according to Mr. Thompson, and many of them must have been towns of large size. Otherwise they could not possibly have possessed the wealth and surplus labor requisite for the construction of temples such as that of Labna, 375 feet long and 3 stories high. Yet Labna is only one of a score of notable ruins lying close together within 15 or 20 miles of Uxmal. All the ruins are massively constructed with carefully dressed stones on the surface and rubble of uncut stones and mortar filling the spaces between the flat-topped, false arches and holding them solid. So firm is the construction, that even in some cases, such as Uxmal, where the lintels were made of zapote timber, which has rotted in spite of its extraordinary durability, the walls have fallen but slightly.

The size and massiveness of the Yucatecan ruins are no more remarkable than are the originality, variety, and delicacy displayed in their adornment. The intricate patterns carved upon the façades of scores of temples and palaces vary most interestingly. In some places one finds massive geometrical designs which are made of rectangular stones jutting out from the face of some lofty wall. Elsewhere large numbers of columns are seen, some being small and purely ornamental, and others large enough to form colonnades. Still another type of adornment consists of huge stone serpents, strange forms of bird and beast, or grinning, distorted human heads set with great teeth. And lastly, the culmination of the ancient Yucatecan art is reached in delicately modeled busts, which can bear comparison with the work of any people except the Greeks and those who have learned from them. At Kabah, a ruin rarely visited by foreigners, two heads, lately exhumed, stand side by side. The plaited hair of these two figures and the high tiaras are not particularly remarkable, although carefully executed. The thing which rivets attention is the skillfully modeled features, the hooked noses, Jewish in outline, but with wider, more tropical nostrils; the curved lips and the sparse, drooping mustaches. The eyes, too, are noticeable, but before one has time to analyze them, his attention is diverted by the curious chain which in each case encircles the left eye, falls down over the cheek, and is brought up to the chin. From the statues I turned to our guide, a Maya Indian, and saw the same features repeated in brown, living flesh. Our Maya driver also had the same hooked nose, wide nostrils, and drooping mustache. The chief difference was in a lesser curvature of the mouth. So well did the old masters work, 1,000 or 2,000 years ago, that although we know nothing of the origin or affinities of the race to which they belonged, we can at least affirm that, in spite of mixture with foreign elements, their blood still flows in Yucatan.

I dwell on these matters in order to emphasize the fact that the ancient Yucatecos were a highly civilized and prosperous race; they were blessed with a large amount of surplus wealth which they could use to support the architects, sculptors, painters, and engineers who superintended the building of the temples and evolved the myriads of ideas which were everywhere brought to fruition. And there was also wealth to support the thousands upon thousands of workmen who quarried the rock, carried it to the buildings, and hewed it to the exact dimensions demanded by the plans of the masters. Other workmen burned the lime with which an army of masons cemented the hewn stones or filled in the great spaces of rubble between the arches. Elsewhere men were toiling to build and repair the cisterns or reservoirs which enabled a large population to dwell in this riverless, springless land of underground drainage. Aside from the throngs engaged in work of a semi-public character, still larger bodies of men must have been busily tilling the soil. Each man raised more food than his own family consumed. To-day, as we have seen, the Indian farmer rarely raises or harvests more than enough for his immediate needs, and his wife literally can not comprehend the value of grinding to-morrow's corn to-day or yesterday. The hand-to-mouth methods of to-day can scarcely have prevailed in the past, for at that time there must always have been a large surplus supply of food which by barter or taxation was available as a store to support the non-agricultural artisans and laborers.

At what time these conditions ceased to prevail no man can tell exactly. When the Spaniards came to Yucatan early in the sixteenth century, the Mayas were much as they are to-day, a slow, mild, and unprogressive people, utterly different from the wideawake, progressive race which alone could have built the ruins. Doubtless they had much of the ancient blood in them, but they made no claim to any knowledge or even any tradition of the construction of the wonderful structures among which they dwelt. Even in so vital a matter as the supply of water they had fallen utterly below the state of their predecessors. In a country such as Yucatan, the water supply is one of the most vital problems. The ancient people were so skillful in conserving water in cisterns and other artificial reservoirs that they built their great cities without reference to the "cenotes" or caves, the only natural source of permanent supply. At the time of the Conquest, however, the Spaniards found practically all the Mayas clustered about the "cenotes" and dependent upon them for water. They had utterly degenerated from the vigor and originality of their ancestors, and were much more different from them than the modern Greeks are from their ancestors in the days of Plato and Phidias. The modern Yucateco does not begin to have the energy and initiative of the modern Greek, but it is probably no exaggeration to say that his predecessors were the equals of the Greeks or any other race so far as real achievement is concerned. I know that this is a sweeping statement, and I shall return to it later. Here it is enough to point out that the Greeks borrowed much of their culture from their neighbors; the Mayas had no one from whom to borrow. The Greeks had at their command the accumulated store of knowledge and of tools from half a dozen great nations; the Mayas had only their own culture and their own crude tools to rely on. Each of these two nations was great because it was full of new ideas. We know the ideas of the Greeks not only from their ruins, but from their books. Those of the Mayas are known only from their ruins, and yet those ruins show that in art, architecture, and the allied crafts, brilliant ideas must have been as numerous as among the Greeks.

The genuine greatness of the ancient Yucatecan civilization deserves as much emphasis as does the degeneration of their successors. The measure of a nation's greatness is found by dividing its achievements by its opportunities. Let us attempt to sum up the achievements of the ancient Mayas. In the first place they developed a system of art and architecture which need not shrink from comparison with that of Egypt, Assyria, China, or any other nation prior to the rise of Greece. Secondly, they appear to have developed a system of communications much easier than would exist to-day except for the railroads. Otherwise they could not possibly have maintained so high a state of civilization. Then, again, they had a highly advanced system of water-supply. In the days before the discovery of iron, deep wells could not be dug and primitive people could live nowhere except close to the deep caverns of the cenotes, or beside the temporary "aguadas" or water-holes. Yet the main ruins have nothing to do with cenotes or natural aguadas. They are often miles from them and are located in places where the only modern water-supply comes from wells 150 to 250 feet deep. Apparently cisterns were constructed on a large scale, as may be inferred from a few which still remain almost intact. Evidence of another kind of high achievement is found in the size of the cities. People who could live in such vast numbers and could carry on such great public works must have had a highly organized and effective social and political system; otherwise chaos would have ensued. And finally the ancient Yucatecos are thought by some authorities to have been on the point of taking one of the most momentous steps in human progress. They had developed a system of hieroglyphics, and were apparently beginning to evolve the use of a definite character to represent a definite sound, instead of a character for each separate word, a step which the Chinese, able as they are, have never taken.

The more one studies the problem, the more one feels that the ancient Yucatecos were full of new ideas; and in the last analysis ideas are the cause of human progress. It is possible, to be sure, that the seeds of some ideas, such as hieroglyphic writing, came originally from the eastern hemisphere—from Egypt perchance, or China, or some other part of the Old World. We can not here discuss this view, although it seems to be far from proven. This much, however, will be admitted, even by those who accept it: the connection between the Old World and the New, if any ever existed, was brief and one might say almost accidental. There was quite surely no such thing as any prolonged intercourse whereby for centuries ideas and methods of thought and action were transferred across the water. They will also admit that the wonderful ruins of Yucatan and of the neighboring Maya areas are distinctly Mayan in style. Whatever may have been imported from other parts of the world had remained long in Central America and had been remodeled to fit the genius of the old American race before it became fixed in the great structures which now arouse our admiration. Mayan ideas in art, Mayan methods of supplying water in a land where there is no surface water, and Mayan peculiarities of religion and taste had become strongly developed. Therefore we must conclude that even if some race from abroad did originally bring civilization to the land, a matter which most of the best authorities deny, the newcomers did not stagnate and deteriorate, as seems to be the case with modern immigrants to this region after a generation or two. They did not imbibe the tropical languor which ultimately seems to check progress unless there is a continual stimulus from without. They kept on working, and developing new ideas for generation after generation. They had the industry to make some of the world's finest ruins, fashioned of carefully hewn stones and ornamented with wonderful carvings; and they did it all without the aid of iron, and with no apparent stimulus from without. At the most the people of Maya land can scarcely have borrowed from other nations a tenth as much as is borrowed by all modern nations, or even as was borrowed by the Greeks. If any race ever worked out its own salvation, it was the ancient Mayas. To develop so far must have required many centuries, and so we may safely say that the Mayas were once continuously blessed with an activity of mind and body comparable to that of almost any part of the world. The stimulus to such activity can scarcely have come from other countries. Was it something in the fiber of the original race, or was it something in their environment?

Before we attempt to discuss this question, let us measure the achievements of the Mayas by still another standard. Thus far we have confined our attention to the ruins of the relatively dry bush- or jungle-covered portion of Yucatan, but an even greater number lie to the south and southwest as far as Honduras and Chiapas. Many are located in the densest kind of forest. The description of the one rather small ruin of this type which I was able to visit in Yucatan will indicate the conditions in which they are located. Lake Kichankanab, it will be remembered, lies on the edge of the tropical forest, equidistant from the Gulf of Mexico on the west, the northern shore of Yucatan on the north, and the Caribbean Sea on the east, 100 miles from each of them. The difficulty of making clearings and the virulence of malarial fevers cause the inhabitants to be limited to a few widely scattered, barbarous Indians and a temporary population of "*chicleros*," or men who come for a few months to gather the sap of the zapote tree for the purpose of converting it into chewing gum. The chicleros are employed on a great concession, which covers several thousand square miles, but whose headquarters at Esmeralda boast of nothing more than four or five palm-thatched sheds. Starting from this place, we rode a mile along a trail so narrow and blocked with vegetation that the Mexican guides had to hew down almost innumerable dead limbs and lianas, although the trail had been in use only the preceding year. At the top of a small ridge overlooking the southern end of Lake Kichankanab we came upon the little ruins of Elemax. When one of the attendants had chopped away the vines from the first structure it proved to be a mass of stones forming a mound measuring about 65 feet by 35. Clearly there once stood here a solid structure in the usual style of ancient Yucatan, a series of rooms roofed with steep-sided, flat-topped, false arches ending in capstones instead of keystones. The surface stones, both inside and out, were carefully smoothed and fitted, and those on the corners were neatly rounded. Twenty feet away lay a similar mound, 90 feet by 55, and others were located all around. Our guide conducted us to the end of this particular group of ruins. We followed a winding forest trail made by chicleros on their way to find zapote trees which they could tap for gum. The trail, of course, was made without the slightest reference to ruins; moreover, the undergrowth of the forest is so dense that the largest sort of mound 100 feet away would be as invisible as though on the other side of the world; and small mounds are hidden at a distance of 20 or 30 feet. Nevertheless, in the space of scarcely a mile we saw at least 20 mounds. Manifestly, if the vegetation were cleared away many more would be in sight. The guide stated that in his hunting trips he comes across similar mounds very frequently, "everywhere," as he put it. Among those that we saw the great majority were small structures, probably houses, but a few of larger size appear to have been temples. Near the temples stand two structures, now only about 15 feet high, which seem to have been pyramids designed for sacrificial purposes or for some other religious rites. The whole aspect of the ruins is like that of those in the jungle region farther north, save that here in the forest the degree of destruction is greater and the original magnificence less. It is possible that all of the houses were not occupied at once, but even if this is so, the ruins clearly represent a considerable population of permanently settled agricultural people who went to the trouble of hewing stone for their temples and other public structures. They must have cleared the forest and raised crops in the clearings permanently.

Similar and far more striking phenomena in other parts of the Maya country point to an even denser population in the deep forests. For instance, Palenque, in the Mexican state of Chiapas, southwest of Yucatan, and Tikal, farther to the east, are famous as the sites of some of the most magnificent ruins in America, ruins which not only are massive, but are beautifully and elaborately carved. They are located in what is described as the densest kind of tropical forest. The size of the ruins and their large amount of sculpture indicate that the surrounding cities must have been long inhabited by a dense population. Moreover, the people must have been highly industrious or they never could have accomplished such great results, especially when they had no iron tools to aid them—nothing but stone, so far as has yet been determined.

All this may perhaps seem alien to our main subject of changes of climate, but it is by no means so, for it raises a great question. To-day, as we have seen, the dampness of the forest, its equable temperature, its fevers, and its over-exuberant vegetation prevent its conquest not only by the primitive Indians, but by the Mexicans or the Spaniards. Nowhere, under similar conditions, has any modern race succeeded in really overcoming the tropical forest as distinguished from the tropical jungle. Yet long ago the ancient Mayas must have cleared and cultivated great areas of what is now dense forest beyond the power of modern man.

Let us turn back now to the other factor in the equation of a nation's greatness, the opportunities which serve as the divisor of the achievements. Of the outward helps which we modern nations deem necessary to great accomplishment the Mayas had practically none. They possessed, to be sure, a country capable of raising abundant crops and supporting a large population. Of other natural advantages, at least of those commonly recognized as such, they had practically none. We have already emphasized the fact that Yucatan is so isolated that without modern means of communication she would even now have no neighbors from whom she could gather suggestions or who would stimulate her by example or immigration. If we consider the entire Maya country, the same is true. The only neighboring region which could possibly have stimulated her is Mexico, but the Zapotecan, Nahua, and other civilizations of that country by no means rivaled that of Maya land, and most of them appear to have been her imitators rather than her examples.

Two other matters are even more important than the lack of any people from contact with whom the Mayas might have profited. These are the complete absence of beasts of burden and of iron tools in pre-Columbian days. In previous pages we have seen the almost immeasurable disadvantage of the nation which lacks these two fundamental aids to progress. The Mayas must have toiled incessantly in carrying on their backs the stones, mortar, and beams of their buildings. Yet this did not check their work. They had no hesitation in transporting stones 8 or 10 feet long, although this must have required laborers by the score. Moreover, all the food of the people, not merely that of the farmers but that of the city people and of the thousands of workmen engaged in building the ruins, had to be brought from the fields on the backs of human animals, a task which only a nation full of energy and resolution would or could accomplish. The absence of beasts of burden, however, was a small matter compared with the absence of iron. We are told sometimes that the ancient Americans had tools of hardened copper, but this is pure theory. We have never found an ounce of such copper and we do not know how it could be made. The sole reason for assuming its existence is that we do not see how the ancient people could have done such clever work without some such material. We fail, however, to appreciate the fact that tools of obsidian or flint can be made of great delicacy by a people who have sufficient skill, energy, and patience. In these last words we come once more to the crux of the whole matter. The Mayas possessed such a degree of mental and physical energy that, in spite of obvious disadvantages, they took the crude tools at their command and were able to arrive at a stage of civilization which was possibly higher than that attained by any other race with no larger opportunities. Their achievements, when measured absolutely, fall far behind those of Greece, and still more, perhaps, behind those of the modern nations of Europe and America, but when measured according to their opportunities, their achievements seem to be worthy of comparison with those of almost any race.

Leaving aside the many mooted questions concerning the ancient Mayas, let us sum up one or two points which stand out with especial clearness. In the first place, the natives of Yucatan, which is at present the most favored part of Maya land, are to-day slow and inert, not given to exertion of any kind, and not in the least inclined to develop new ideas and bring them to fruition by arduous labor. In the second place, European immigrants quickly acquire the inefficient habits of the natives, and in two or three generations appear to cease to be energetic enough to carry out new ideas although they may perhaps have them. In the third place, the conquest of the tropical forests is a task beyond the power of any of the modern tropical races, even though they have good steel tools to help them. Moreover, it is doubtful whether any European race could as yet conquer the forest and raise crops in it in the face of the enervating climate and the debilitating fevers. In the past, however, the exact contrary was true in respect to all three of these points. The natives of Yucatan were not slow and inert, but were highly inventive and energetic.

Immigrants from other regions, if such were really the bringers of the seeds of civilization, did not degenerate rapidly, for their descendants must have been full of energy and initiative for centuries before a culture so highly impregnated with local character could have developed. And finally the ancient people succeeded in conquering regions that now are unconquerably forested and feverish.

In order to explain this strange contradiction between the past and the present two possibilities present themselves. The first is that the ancient inhabitants of Yucatan, in spite of their lack of beasts of burden and tools of iron, could accomplish all manner of things which modern man can not. They could clear and cultivate the dense forest, they could resist its debilitating fevers, they could work with constant energy in spite of the enervating climate, and they could persist in doing all these things for centuries. In other words, they were greatly superior to any modern race. This is the common, although unexpressed assumption. The other possibility is that the rainfall was formerly less than at present, so that regions now covered with forest then bore only jungle, that fevers were less abundant than now, and that the climate was not so enervating. This second possibility seems to demand less radical assumptions than the first. It simply requires us to believe that the same sort of thing has happened in Yucatan which we have reason to believe has happened elsewhere.

A

B

C

D

A. Carved head at Baul in the Pacific coffee belt of western Guatemala

B. Fragment of a temple wall at Copan.

C. One of the Stelae at Copan.

D. Forest in which the ruins at Kichen-kanab are located.

CHAPTER XVI.

THE SHIFTING OF CLIMATIC ZONES.

In the preceding chapters we have seen that in few parts of the world is there a greater contrast between the past and the present than in Yucatan and the surrounding regions of Maya culture. This is preëminently the case in those districts where magnificent ruins are located in the midst of dense and uninhabitable forests. We have seen further that the ancient Mayas were undoubtedly a remarkably efficient people, in striking contrast to the notable inefficiency of the present inhabitants of the torrid zone and especially of the inhabitants of densely forested areas. Furthermore, according to the overwhelming evidence of the ruins the Mayan culture developed where we now find its traces, and this development must have demanded many centuries of growth previous to the many centuries during which it bore fruition in the great temples and cities whose remnants we now admire. These facts lead to the further conclusion that if the physical conditions of Maya land were the same in the past as in the present, the ancient Mayas, in sharp distinction from their descendants, must have possessed a degree of energy and a power of resistance to the debilitating effects of a tropical climate far in excess of that of any other race now existing. This is certainly a possibility and can not be lightly dismissed. It is one of those possibilities which can not be proved and which are often adopted as a refuge when all other theories fail. Other possibilities, such as the introduction of culture from the eastern hemisphere or the invasion of Maya land by some alien race possessed of an uncommonly high culture, are more and more being universally negatived by the work of recent scholars. Still another, and (so far as now appears) perhaps the only other genuine possibility is that in the past the climate was so much drier than now that the present forested areas were covered merely with jungle instead of with large trees. Such an assumption at first sight appears to be directly opposed to our general conclusion that the southwestern United States and central Asia are now on the whole distinctly drier than in the past, but such is by no means the case. Let us first see how much ground there is for believing that climatic changes of any sort have occurred in Yucatan. Then let us investigate the probable nature and effects of any such possible changes; and finally let us test all our conclusions by the rigorous method of a comparison of the dates indicated by our California curve and the dates of Maya history so far as they have been ascertained.

Writers on Yucatan have sometimes suggested that the country could not formerly have supported so vast a population had not the rainfall and the agricultural possibilities been greater than at present. Others deny this. They say that an industrious and active people who had the energy and brain-power to construct wells and reservoirs could cultivate almost every foot of Yucatan proper except for the numerous spots where the bare rock actually comes to the surface. One can ride for days over plains of rich soil, deep, soft, and easy to cultivate, but abandoned to the jungle and to wild beasts. The reason is the difficulty of digging wells or building reservoirs, or else the prevalence of fevers. Except for an insignificant coastal strip where no ruins are found, Merida is as dry as any portion of Yucatan; yet the five months of the rainy season from June to October have 26.5 inches of rain, which is decidedly more than the eastern United States gets during the same period and is sufficient to allow good crops of corn to be raised almost everywhere. That lack of rainfall has nothing to do with the present comparative depopulation of Yucatan is evident enough from the fact that the densest and most progressive population is found in the driest part of the peninsula. In fact, as has been pointed out in our discussion of the jungle and the forest, a small rainfall is a distinct advantage, because it prevents the growth of the great tropical forest which so effectively checks human progress. If the rainfall of the past had been greater than that of the present, the effect would have been to diminish rather than increase the density of population.

There appears, then, to be no reason for thinking that Yucatan has suffered a diminution of rainfall similar to that of Arizona or of the portions of Asia in temperate latitudes. Nevertheless, the lakes and terraces of the Valley of Mexico and the great terraces of the state of Oaxaca furnish strong evidence that a marked change of some sort has taken place in those regions; and if such has been the case there, Yucatan, which lies but 500 miles from Oaxaca and from 1 to 4 degrees farther north, can scarcely have failed to be affected. At these southern points, however, the effect need not necessarily have been of the same type as that produced farther north—in New Mexico, for example—since the two places lie in different climatic zones.

The general effect of changes of climate seems to be to shift the peculiarities of one latitude into another or, perhaps more accurately, to cause the seasonal shifting of zones to vary in amount and intensity. Inasmuch as the chief change during the past 2,000 to 3,000 years in the regions 30° to 40° north of the equator appears to have been in the direction of aridity, the general shifting seems to have carried the conditions of more southerly regions into those farther north. This would seem to mean that at the beginning of the Christian era or earlier the zone of westerly storms, during the winter, but not necessarily in summer, lay farther south than to-day, and thereby made the present subtropical zone less arid than at present. The natural corollary of this would be that the subtropical zone of aridity was also displaced southward. This would have led to a diminution of winter rainfall and hence of vegetation along the northern edge of the equatorial zone in those parts where inblowing trade winds combine with equatorial low pressure to produce abundant rain at all seasons. Thus jungle would have been caused to take the place of genuine, dense forests in those particular regions, and jungle might in turn be replaced by bush. In Yucatan and other parts of the extreme south of Mexico, or in Central America, the transition from jungle to forest is often quite sudden. For instance, in Yucatan it occurs within a distance of 30 to 40 miles. If the line of transition were shoved southward 200 to 300 miles, it would cause jungle to prevail in practically all the places where ruins are now found.

Such a change as has just been described would not merely explain the location of great ruins in regions now too densely forested to be habitable; it would also to a certain extent relieve us of the necessity of assuming that the ancient Yucatecos possessed a degree of energy and ability out of harmony with anything which now exists in regions so warm and debilitating as Yucatan.

Before explaining this, however, it will be well to examine more closely the probable mechanism of a shifting of the great climatic zones. This can best be understood by considering first what happens during our ordinary winters. Most of the rainfall of the United States, as everyone knows, is derived from cyclonic storms—that is, from great areas of low pressure and inblowing winds which may have a diameter of 1,000 or more miles, and which sweep across the country with a general easterly trend in obedience to the prevailing direction of the winds in temperate latitudes. The courses of these storms, so far as they are understood, are determined by the differences in pressure between the several more or less permanent areas of high or low barometer which center over oceans and lands in various latitudes and with varying degrees of intensity at different seasons. In general, storms move out from or around areas of high pressure and are drawn toward those of low pressure. Anything which changes the location or intensity of the major pressure areas changes the course and intensity of storms. The North Atlantic Ocean, by reason of the high degree to which it is warmed by the Gulf Stream, is a most important area of permanent low pressure. To this is thought to be due in large measure the fact that the northern United States and Canada on the west and northwestern Europe on the east, together with the Atlantic Ocean between them, are the most stormy regions of the globe. In summer, when the continents become warm and therefore are characterized by low pressure, the North Atlantic low area loses its importance. The difference in pressure between land and sea is slight, and the storms are correspondingly mild. They move nearly from west to east, although of course with many curves, and their tracks are usually located well up toward the north. In winter, on the contrary, the continents cool off and become areas of pronounced high pressure, while the oceans are areas of low pressure. At this time the difference in pressure between North America and the North Atlantic reaches a maximum, the barometric gradients are steep, and storms are correspondingly fierce. The courses of the storms under such conditions are more curved than in summer and lie farther south. The center of the continent becomes so cold that an extensive area of permanent high pressure is formed; from this the winds blow outward. Thus the storms which would otherwise move more or less directly east from the Pacific to the Atlantic are pushed in many cases far to the south. Starting in California, a storm may swing southeast into Arizona and Texas, and then move east and finally come up the Atlantic coast and swing off toward the low center of the North Atlantic. In its wake such a storm may send the thermometer down to 20° F. in southern Arizona and kill the peach blossoms which have opened too early; then it may go on to produce a "norther" with a temperature of 50° in Yucatan, and to kill the orange trees in Florida. The number of storms which follow such southerly courses varies greatly from year to year. Upon these variations the character of the winter largely depends. In 1911–12, for example, the northern parts of the United States had few storms and slight snowfall as a general rule

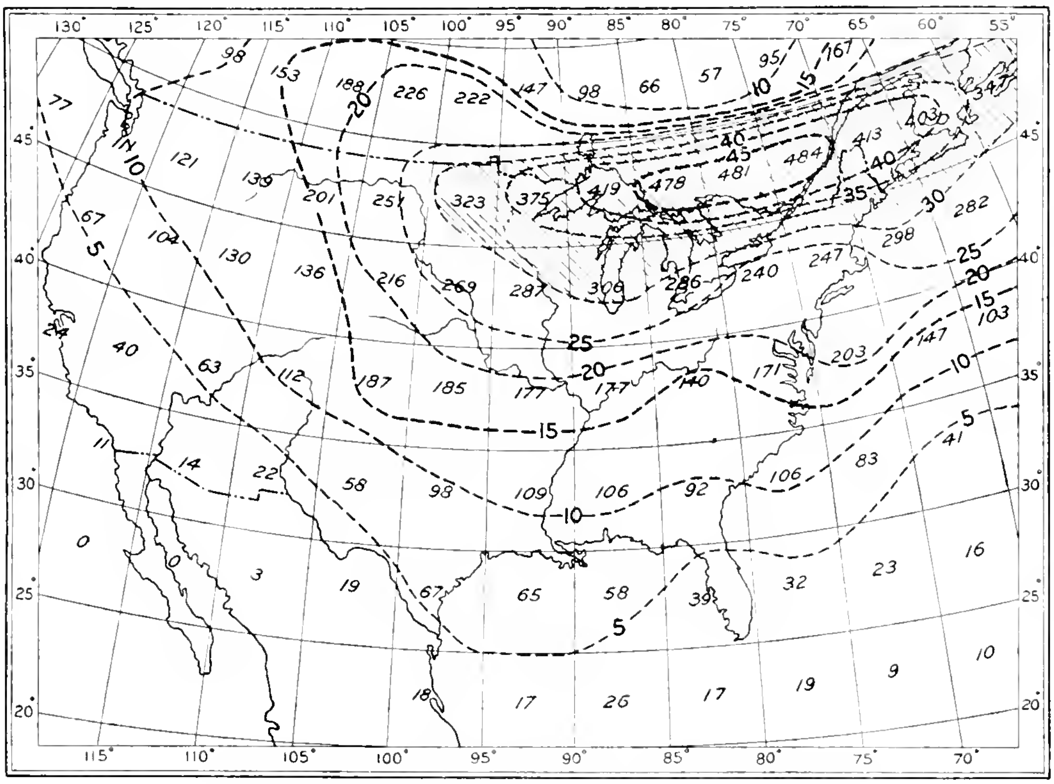


Fig. 51.—Storm Frequency, 1878–1887. (After Dunwoody.)

during the middle of the winter, although this was compensated for toward spring. Farther south, however, storms which had gone far equatorward brought to Texas and northern Mexico more than the usual amount of rain, while Yucatan also had a comparative abundance of showers and of "northers." The conditions were by no means remarkable, but they serve to illustrate the fact that variations in the tracks of the storm bring with them important results in the way of variations in rainfall and temperature. The winter of 1911–12 was characterized by a relatively pronounced and long-continuing area of high pressure over the central part of North America, and therefore the storms for a season went far to the south. In 1912–13 exactly the reverse took place. The continental high-pressure area was poorly developed, the storms moved over northerly tracks, and the northern United States was uncommonly warm.

Having seen that the general course of the storm tracks varies from year to year, our next question is whether, if longer periods than a year are considered, the average track shows any variation. Dunwoody some years ago began the investigation of this matter, and, so far as data were available, made a map, figure 51, showing the average number of storm centers passing over each 5 degrees square of the northern hemisphere. His map shows that the number of storms is greatest in the region of the Great Lakes of North America, and is large throughout all of the northern United States, southern Canada, northwestern Europe, and Japan. Professor C. J. Kullmer, of the University of Syracuse, has made a study of this map and has pointed out that it affords some most interesting suggestions as to the possible relation between high civilization and climatic instability. In a later publication I shall consider this matter at length, but for our present purpose the important matter is that his work enables us to compare the storm tracks at two periods separated by an interval of 12 years. Inasmuch as his original data have never been published, and as they are important not only for our present purpose, but for other climatological studies, I have persuaded him to prepare the contribution which follows.

THE SHIFT OF THE STORM TRACK.

By Charles J. Kullmer.

Our only maps of the storm frequency of the whole of the northern hemisphere (we have none of the southern hemisphere) are those of H. H. Dunwoody, published in 1893, and covering the 10-year period from 1878 to 1887. The storm frequency is given in separate maps for each month, and these are combined into a year map. Dunwoody divides the map of the northern hemisphere into squares measuring 5° on a side and records in each square the number of barometric depressions whose centers crossed it during the period under discussion. For instance, the centers of 306 depressions passed through the Lake Michigan square, or about 30 barometric depressions a year. Practically the storm frequency was much greater than this, since 419 storms passed through the Lake Superior square on the north and 177 storms in the square just south; but this need not concern us, for we have here to do only with the tracks of the *centers* of depressions. In view of the importance of storms in many phases of life, it has seemed worth while to reconstruct the storm frequency maps for the United States for the latest available decade, 1899–1908, in order to determine whether in the interval of 21 years any general shift of the storm track has taken place. The material for this is available in the plotted tracks of barometric depressions given in the monthly summaries of the "Monthly Weather Review."

Dunwoody does not give the individual tracks, nor does he describe in detail the methods used in constructing his charts, so that there is some doubt as to the extent to which his material may be considered identical with that used in the present investigation. A comparison of the maps and a discussion of the results, however, seems to show that the material is in general the same and that reliable comparisons are possible.

The monthly maps of the United States for the new series of observations as compared with the old are given in figures 52 to 63. In these the figures represent the number of storm centers for each 5° square, those of Dunwoody for 1878–1887 being placed above, and those of the later period, 1899–1908, below. The curved lines represent the number of storm centers passing through a given square each year, the earlier conditions being indicated by dotted lines and the later by solid lines. In the first map, that for January, figure 52, we at once find five important phenomena, which occur also on later maps and on the year map; first, an increase in storm frequency over the southwestern States; second, a decrease in the west in latitude 40° to 45°; third, a great increase in western Canada; fourth, a general southerly movement of the lines of equal storm frequency; and fifth (and perhaps most interesting), the phenomenon of a double maximum in latitude 45° to 50° as compared with the single maximum of the earlier period. The great increase in western Canada is of such an amount as to suggest a difference in the observational material, but this is not necessarily the case, as will appear later.

The February map, figure 53, shows all the phenomena of that for January. The southwestern increase in storm frequency is especially marked, the number of centers passing through a single square having in one case increased from 9 to 32. Just to the northeast of this square the western decrease in latitude 40° to 45° is also quite pronounced. The increase in western Canada and the southerly shift of the lines as a whole are nearly as marked as in the January map, while the double maximum is less distinct, although it clearly exists. March (figure 54) shows most prominently the southwestern increase, while the general southerly shift is visible, and the double maximum still appears, although

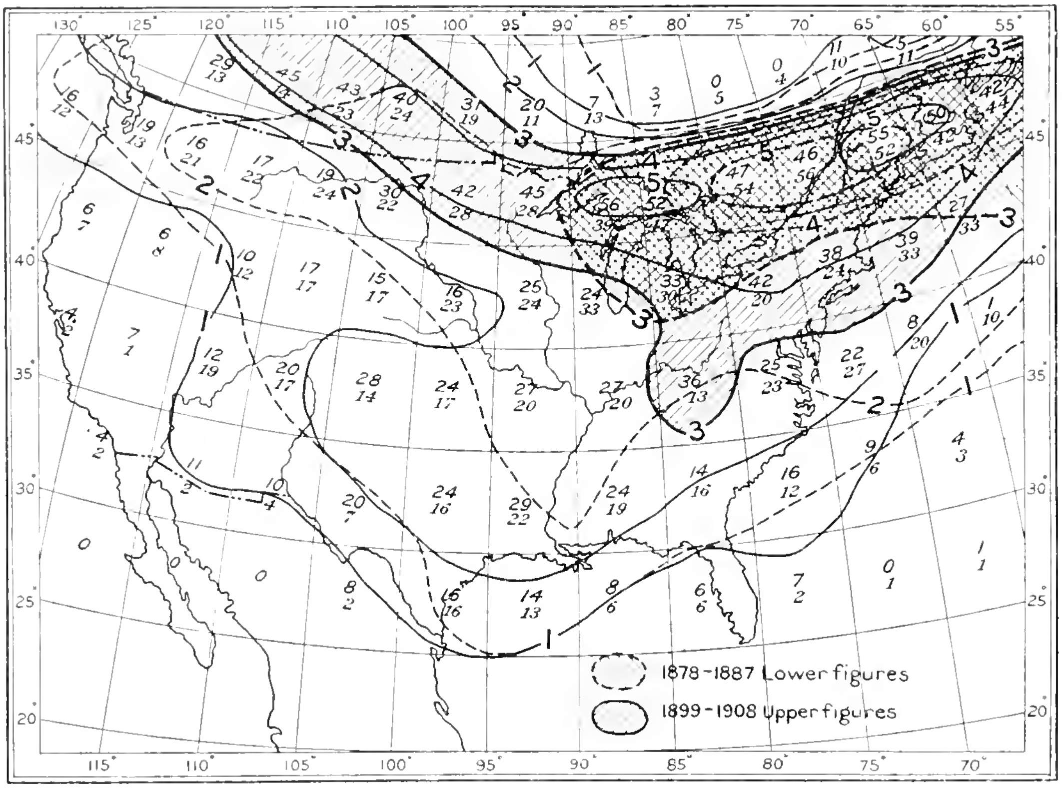


FIG. 52.—Storm Frequency. January.

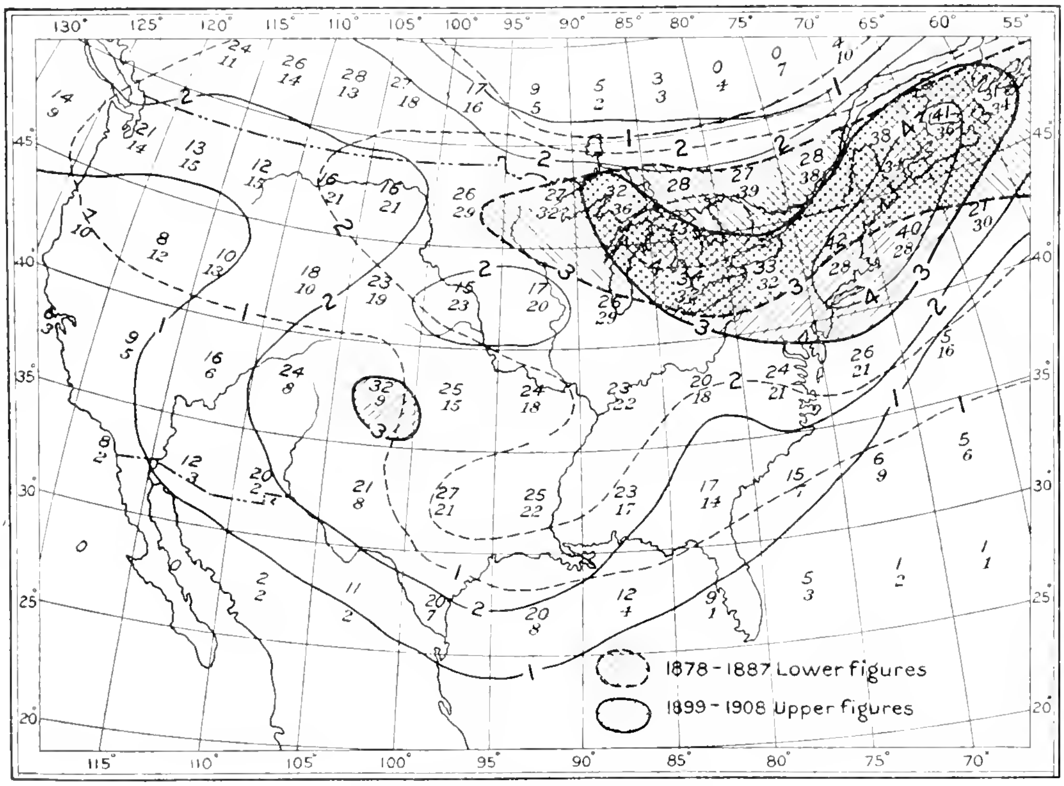


FIG. 53.—Storm Frequency. February.

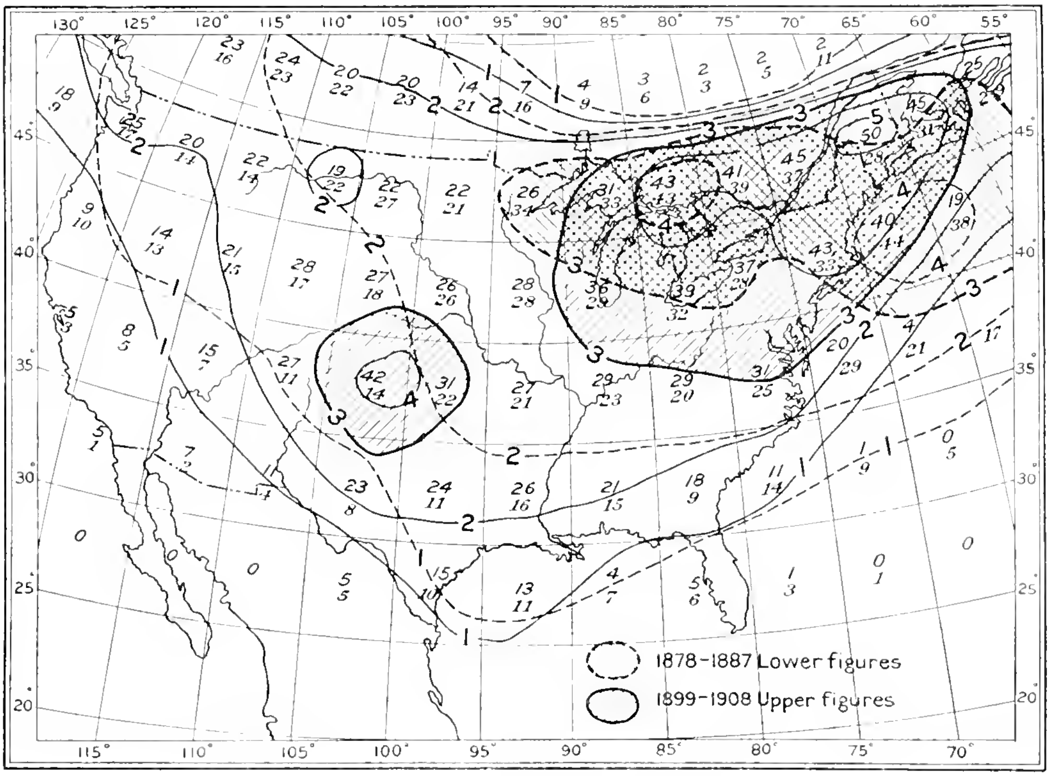


FIG. 54.—Storm Frequency. March.

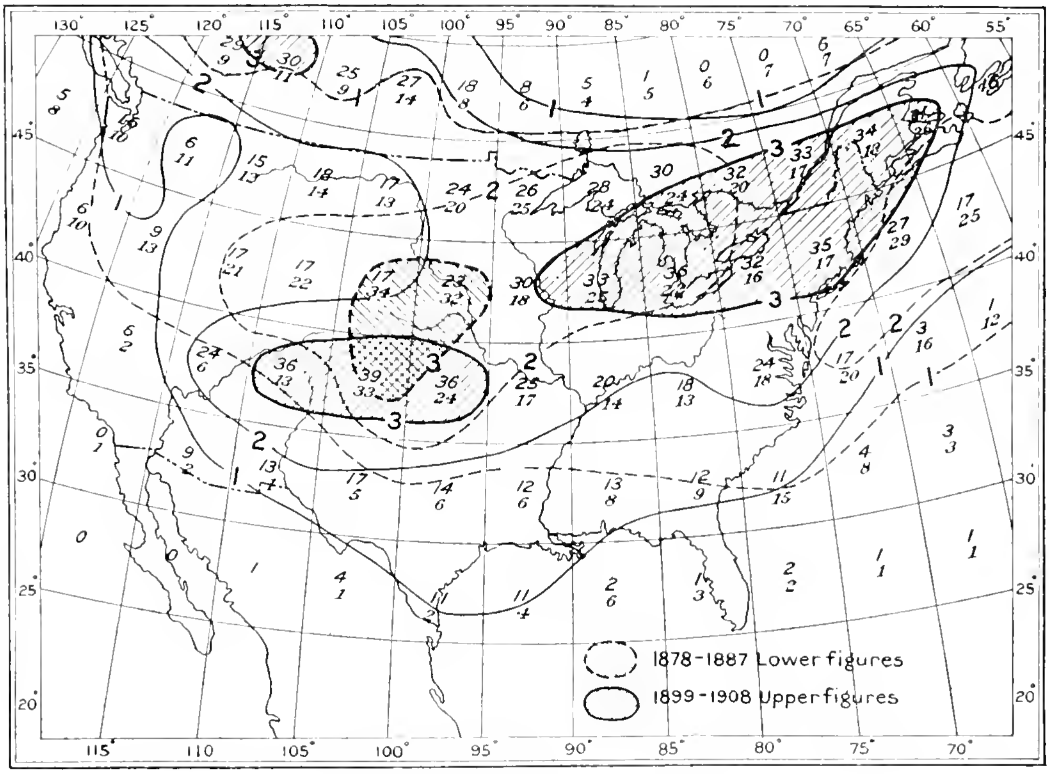


FIG. 55.—Storm Frequency. April.

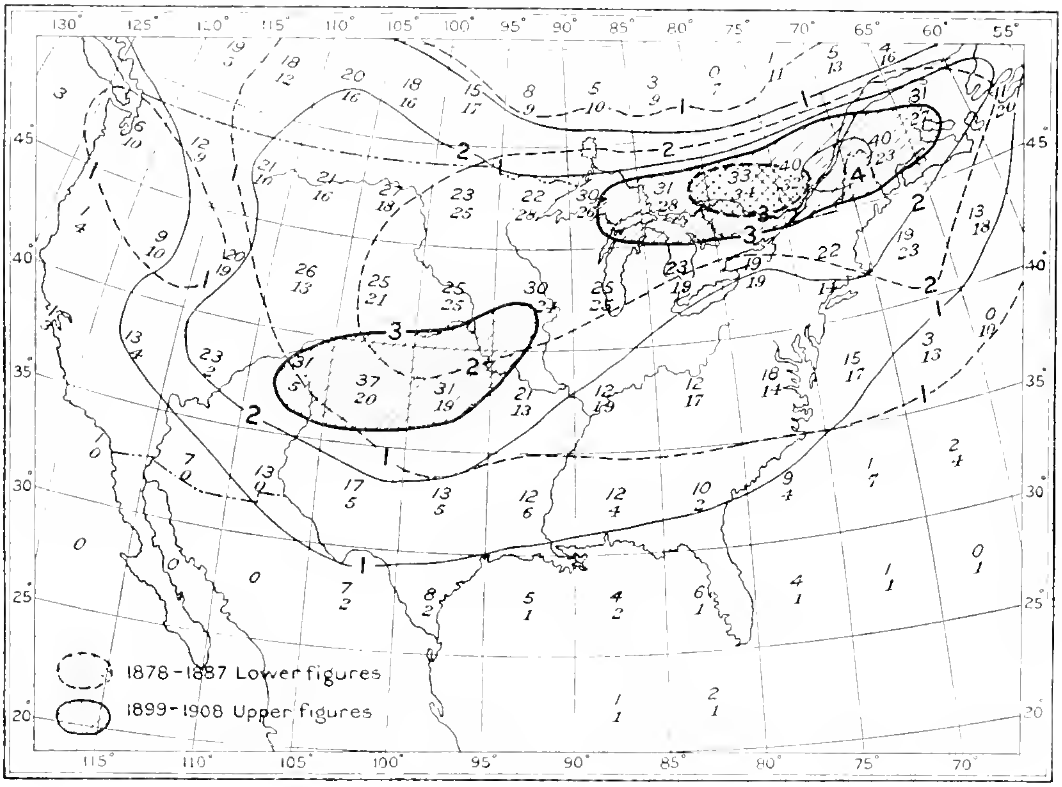


FIG. 56.—Storm Frequency. May.

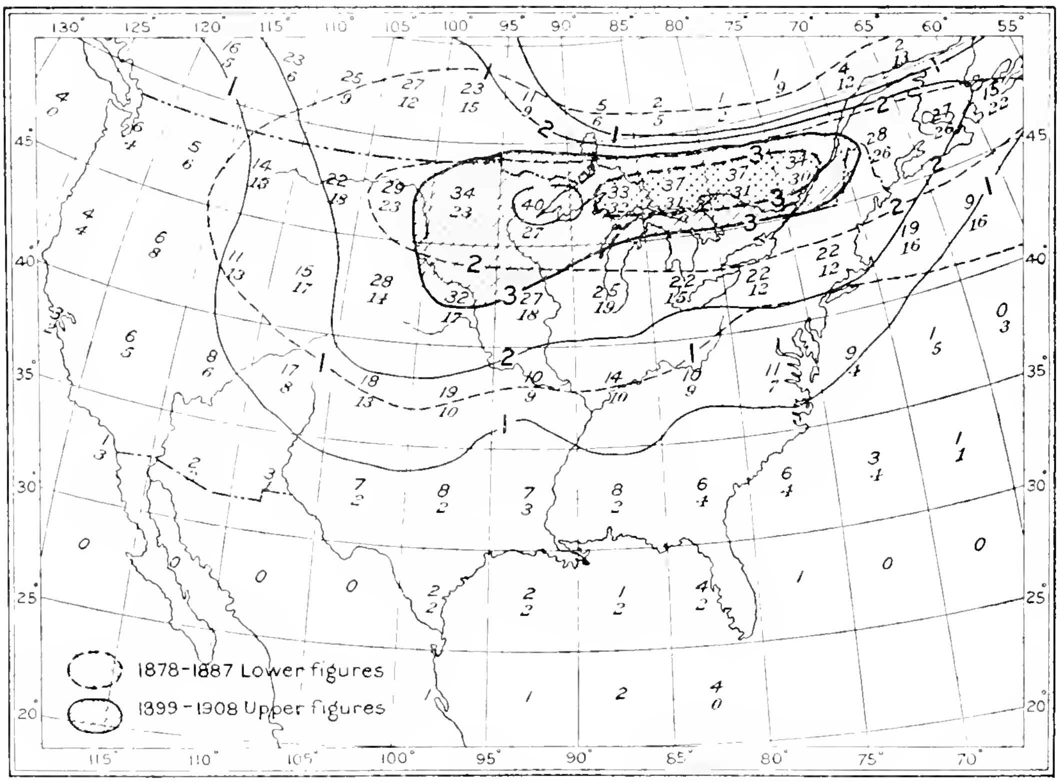


FIG. 57.—Storm Frequency. June.

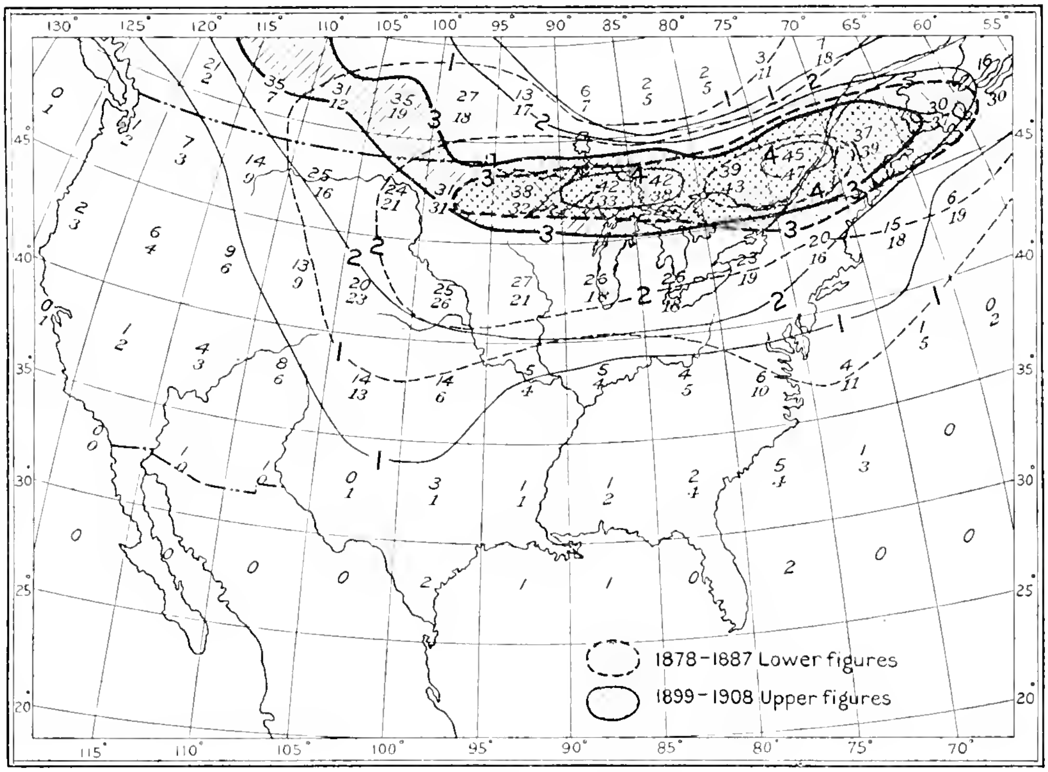


Fig. 58.—Storm Frequency. July.

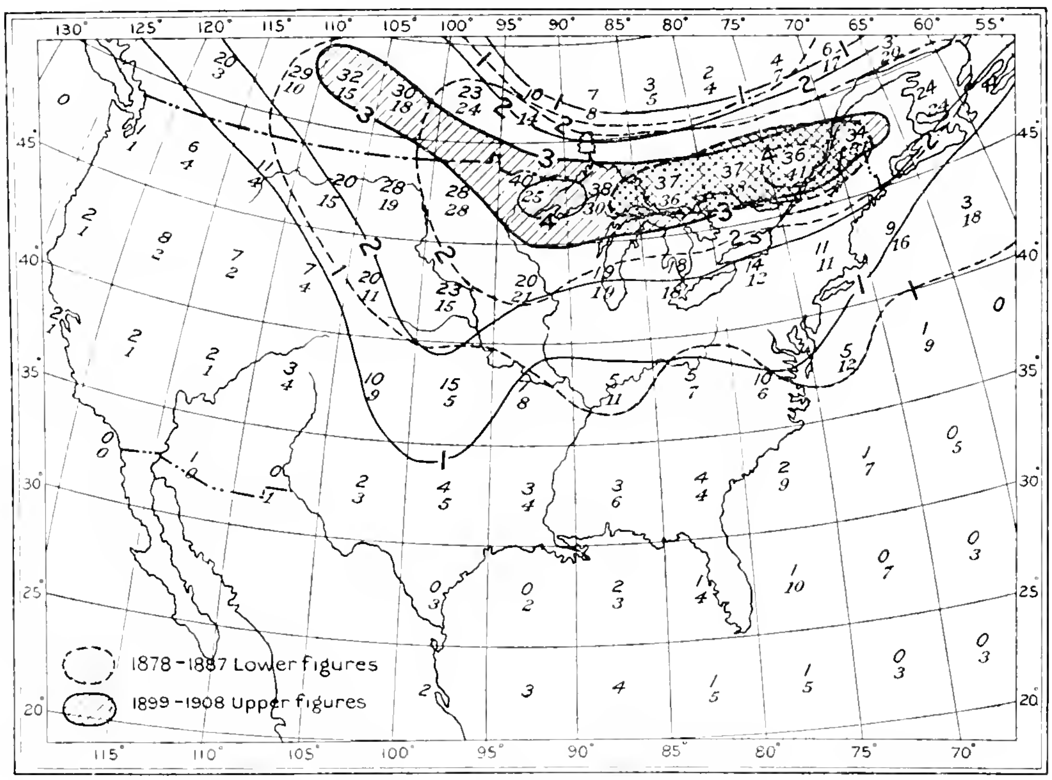


Fig. 59.—Storm Frequency. August.

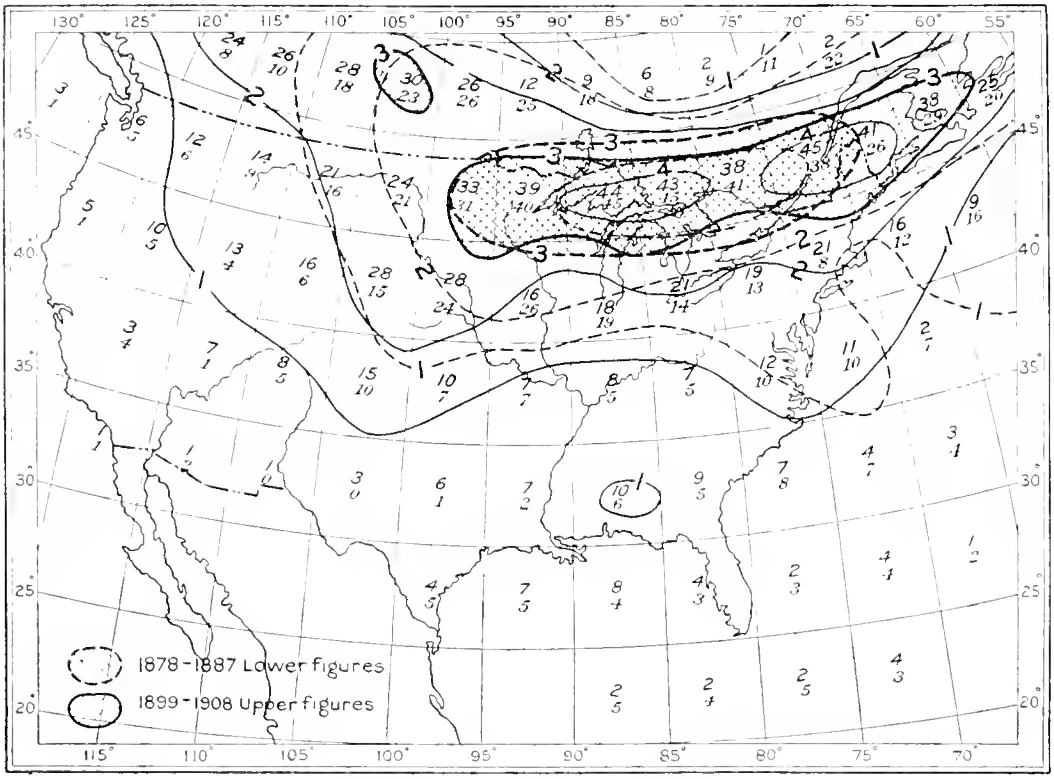


FIG. 60.—Storm Frequency. September.

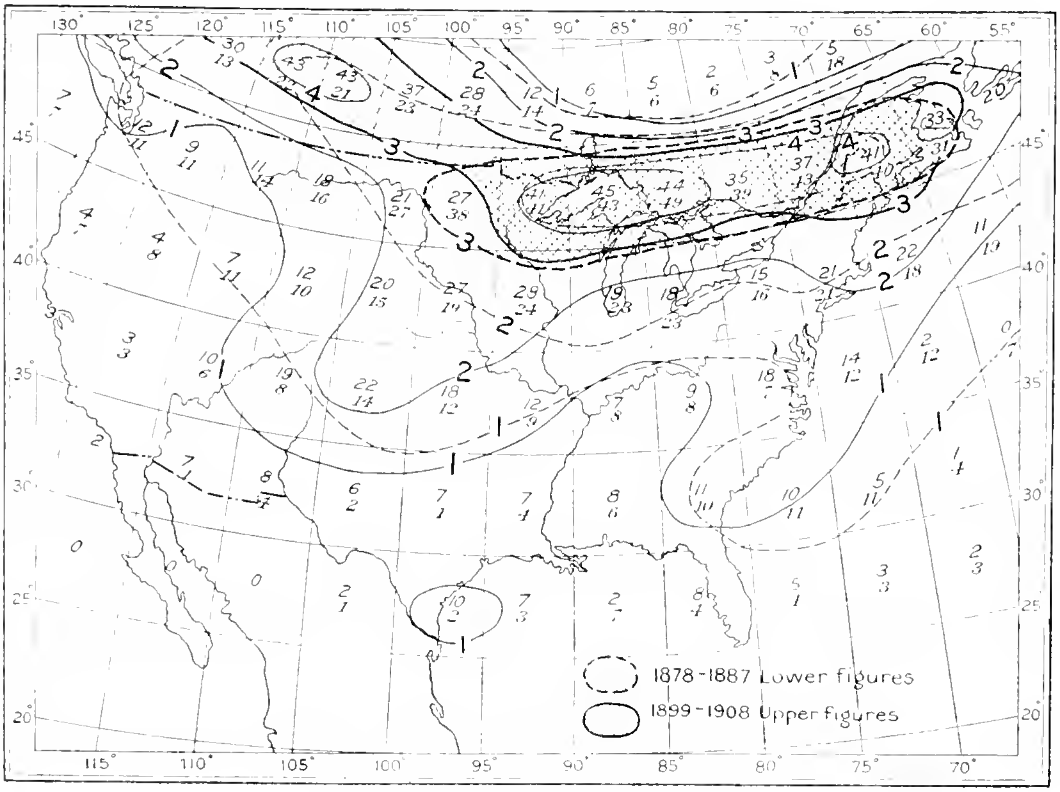


FIG. 61.—Storm Frequency. October.

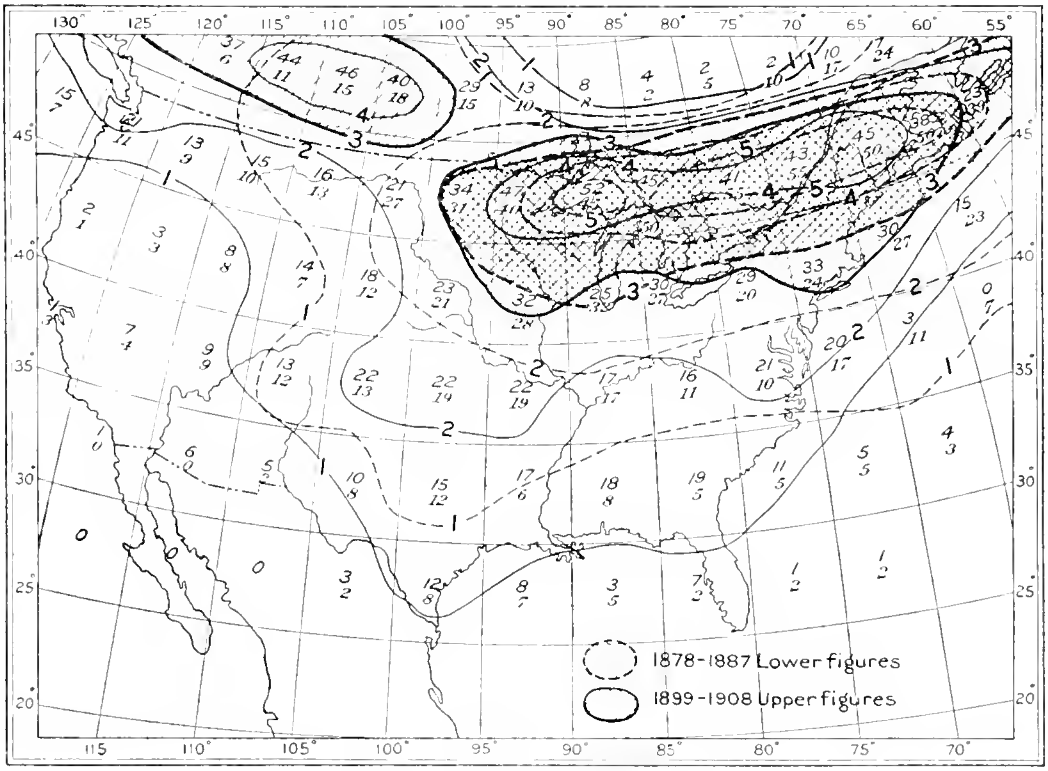


Fig. 62.—Storm Frequency. November.

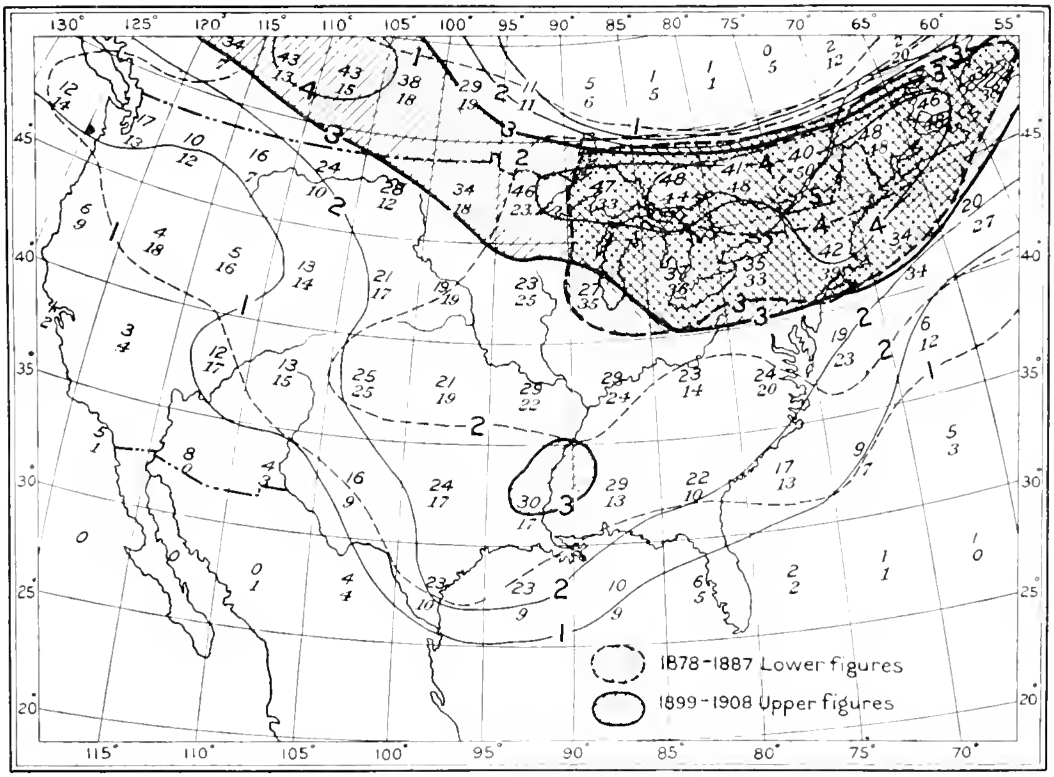


Fig. 63.—Storm Frequency. December.

its eastern member has moved one square west of its position in February. The western decrease, however, and the Canadian increase have both disappeared almost entirely. This speaks strongly against the idea that the differences between the old and new series of maps are due to differences in the observational material on which they are based. If such were the case it would scarcely be possible that in one particular month there shou d be a sudden reversal of previous conditions, so that the number of observations should suddenly show a relative increase in the western United States in latitude 40° to 45° and a large decrease in Canada 10° farther north. The April map for both periods (figure 55) shows a southwestern maximum; in the later period, however, the center lies farther south and west than in the earlier. In this map we again note the decrease north of the southwestern increase, and the western Canada increase. Each period shows only a single eastern maximum, that of the later map lying well to the west of the other.

May (figure 57) shows the southwestern increase and a slight decrease in the Oregon-Idaho section. Here again we notice only a slight increase in western Canada, which gives strength to the reality of the large increases shown in other months. Also the double maximum has almost disappeared, although traces of the western center may be seen in the 27 tracks which crossed the square between 45° and 50° N. and 100° and 105° W. In this case the earlier map also showed a double maximum indicated by the figures 28 in the square between 90° and 95° W. and 34 between 75° and 80° W. June (figure 57) shows marked western Canadian increase, a moderate southwestern increase, a double maximum, a slight western increase, and a distinct southward shifting. July (figure 58) shows strong western Canadian increase, double maximum and southwestern increase. August (figure 59) shows western Canadian increase and a westward shift of the maximum in latitude 45° to 50°. September (figure 60) shows general westward shift, double maximum, and western Canadian increase. October (figure 61) shows the southwestern increase, the decrease just north of it, a pronounced increase over western Canada, and a double maximum including within it a double maximum of the earlier period. The agreement of the peculiar loop in the southeastern part of the 1 line in both maps is striking. November (figure 62) presents the highest increase over western Canada, a double maximum as compared with the single maximum of the earlier period. The same holds also for December (figure 63). The Oregon-Idaho decrease is here marked. There is also a general southerly shift.

Combining these month maps we have a year map (figure 64), showing general agreement with that of 21 years before, but characterized by the phenomena already noticed in the month maps—a marked increase over western Canada, a slight decrease in the two western squares of latitude 40° to 45°, and a general southerly and westerly shift of the lines of equal storm frequency. In latitude 45° to 50°, along the storm track proper, a single maximum of 484 in the earlier period is replaced by a double maximum, 480 and 491, in the later period. If we take the central area, which may be supposed to have had 400 storms in each case, its center would seem to fall about 2.5° farther west in the later map than in the earlier. Little reliance, however, can be laid on this. Corresponding to the general westerly shift, an eastern decrease is noted, but I lay less weight on this feature, since I am convinced that the tracks as given in the monthly summaries are not continued over the ocean in all cases as far as might be the fact.

Turning now to the discussion of the meaning of the maps, let us consider first the phenomenon of a double maximum. If the average track of all storms be plotted it forms a curve corresponding to the line of greatest frequency. If such a curved line merely touches a given parallel of latitude, say that of 47° N., there will be a single maximum of storm frequency along that line. If, however, the curved storm track is shifted enough so that its most southerly point lies a few degrees south of latitude 47°, say in latitude 45°, the storm track itself will cut the given parallel in two places. Thus along that latitude we should get a double maximum where previously only a single maximum was found. In the present case the ideal storm track—that is, the mean of all tracks—may be considered as running in a great arc somewhat southeasterly from a point in western Canada, approximately in latitude 55° N. and longitude 115° W., to the northern part of Lake Superior, eastward across southern Canada, and then with a slight northerly trend toward Newfoundland. The area of greatest storm frequency is limited to a small region, approximately 45° to 50° north of the equator. Southward the number of storms decreases gradu-

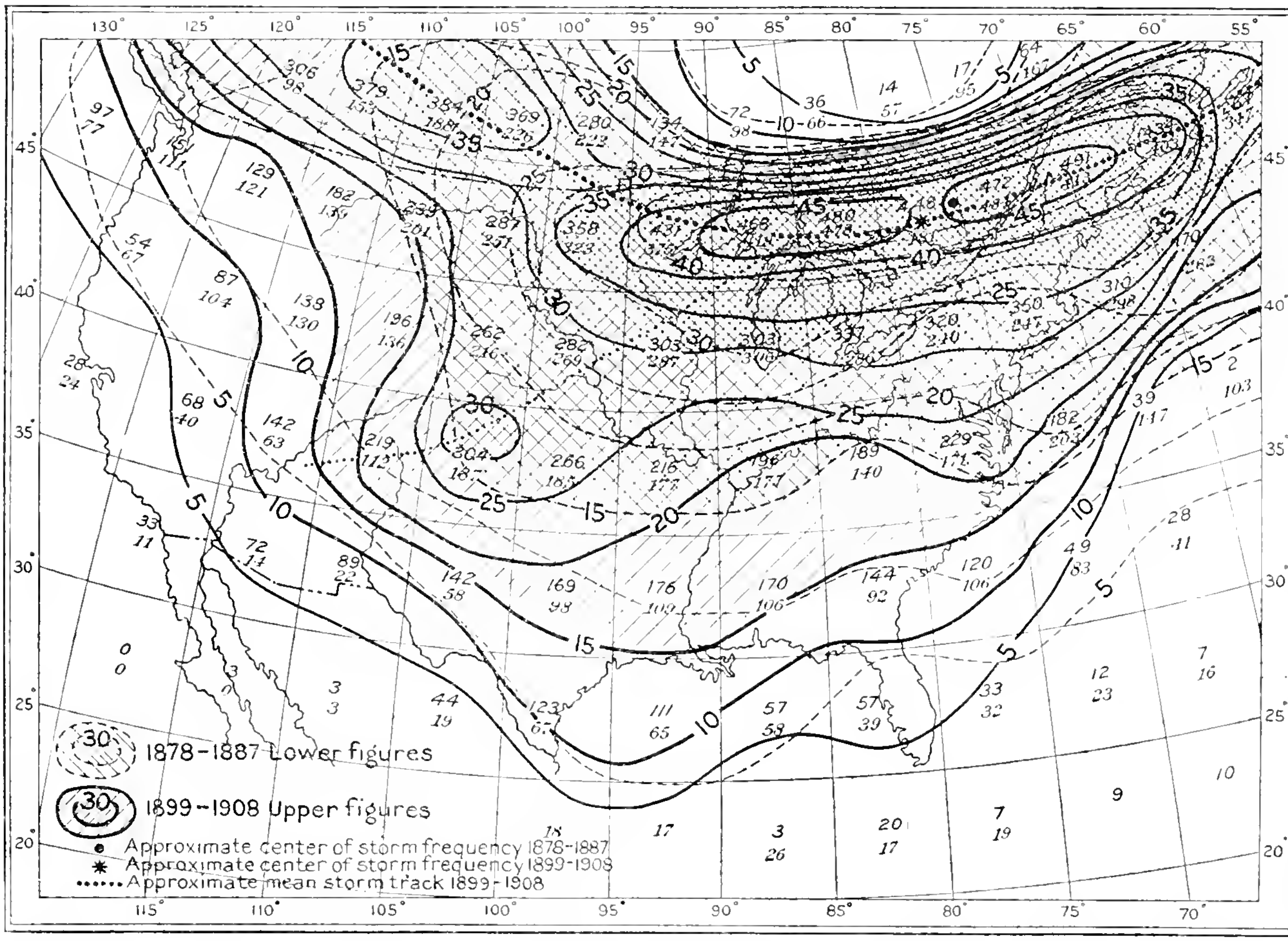
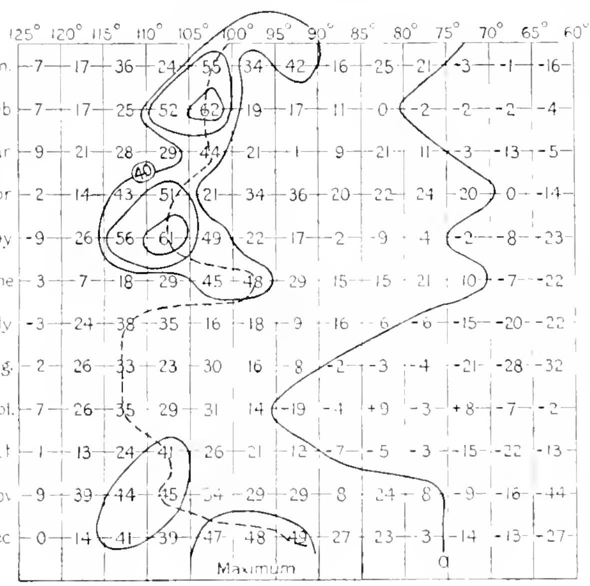


Fig. 64.—Storm Frequency. Year Maps for 1878–1887, after Dunwoody, and 1899–1908, after Kullmer, showing Shift of Storm Track.

ally; northward the decrease is very rapid. A southerly shift of the storm track of this region would cause a decrease in storm frequency in the squares just north of the center of the curve, which is seen to be the case in the map for the years 1899–1908 as compared with the earlier one. At the same time the southward movement of the storms would produce increased storm frequency south of the former mean storm track, which is actually the case, as appears from the increase of 103 in the New York square. Under such circumstances a double maximum might perhaps be produced in this fashion. Suppose that in the earlier of our two periods the curve of the mean storm track were tangent to the parallel of latitude 47.5° N. which, of course, is the mean latitude of the tier of squares 45° to 50° N. Being tangent to this parallel at the most southerly swing of the track and also at the point of greatest storm frequency, we should clearly get a single maximum. If, however, the mean track were to swing somewhat farther south, so that at the extreme southern limit (where, as before, storms were most frequent) it touched latitude 46°, it would cut the parallel of 47.5° in two places. As 46° is not the median line of any set of squares, we should not have any maximum corresponding to it, but we should have a double maximum in the tier of squares having 47.5° as their median line.

Let us turn now to the question of how far the apparent increase in storm frequency during the later as compared with the earlier of our two periods is genuine. The total number of observations of storms, as obtained by adding all the numbers on each of the two year-maps, shows that the total frequency for the later period is 17.4 per cent more than for the earlier. At first it might be thought that this is due merely to a difference either



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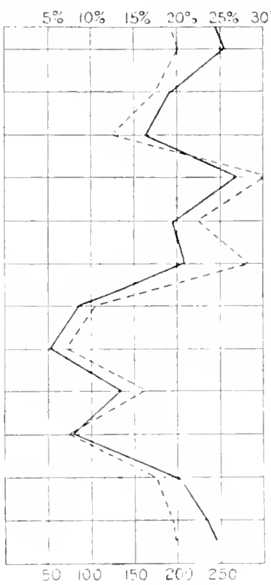

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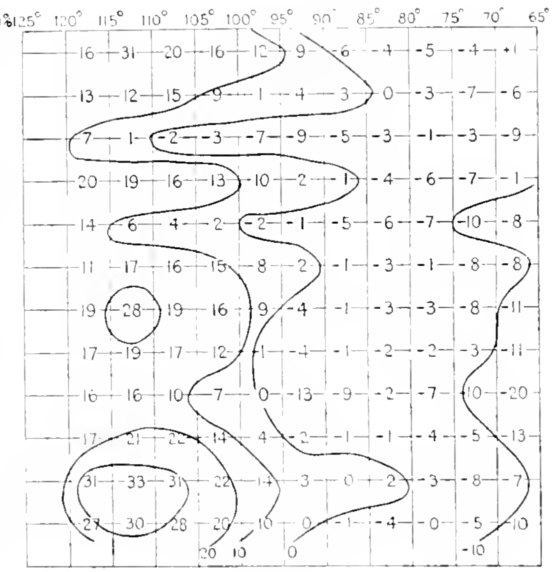

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Fig. 65.—Changes in Storm Frequency by Months according to Longitude.

Numerals indicate amount of increase or decrease in storm frequency in the given longitude for each month. Lines drawn around the areas show an increase of over 40. The line marked "zero" indicates no change in frequency. The dotted line marked "maximum" indicates maximum increase.

Fig. 66.—Changes in Storm Frequency by Months Irrespective of Longitude and Latitude.

– – – = Absolute increase in storm frequency by months.
——— = Per cent of increase. Average per cent equals 17.4.

Fig. 67.—Changes in Storm Frequency by Months according to Longitude in Latitude 50° to 55°.

in the observational material or in the way in which it has been treated. Closer inspection, however, seems to show that this is not the case. If it were the case, we should expect to find that the increase indicated by the later figures is distributed somewhat uniformly over the whole country, and in each of the different months. In order to test this I have plotted the total increases in storm frequency for each month of the year in the solid line of figure 66 and the percentage of increase by a broken line. It is evident that the increase in storm frequency has varied from 7.5 per cent in some months to 30 per cent in others. Moreover, the curve shows a seasonal variation with two periods of minimum increase in the late winter and late summer, and two of maximum increase centering approximately in May and December. In addition to this, I have plotted the increase and decrease for each month of the year in each north and south column of 5° square, as is shown in figure 65. Here it appears that the lines of no increase and of maximum increase both shift eastward or westward according to the seasons, being farthest to the west toward the end of the winter and early in the fall, at about the time when the greatest increase in storm frequency takes place. If the increase in storm frequency for a single tier of squares (that is, for those between two parallels of latitude 5° apart) is plotted, a similar phenomenon is observed in the case shown in figure 67, where the increase or decrease in latitude 50° to 55° has been plotted. Here again the curves are roughly parallel to those of figure 66, a phenomenon whose significance is not apparent, but which seems worthy of study. In latitude 45° to 50°, however, as appears in figure 68, the increase or decrease in storm frequency assumes a character entirely different from that farther north. The diagram shows a peculiar curved area of decrease and a diagonal distribution of increase with a maximum in the east centering during the month of March. The diagrams of this same phenomenon for the other tiers of latitude show an equally variant distribution, as may be seen in part in figures 69 and 70.

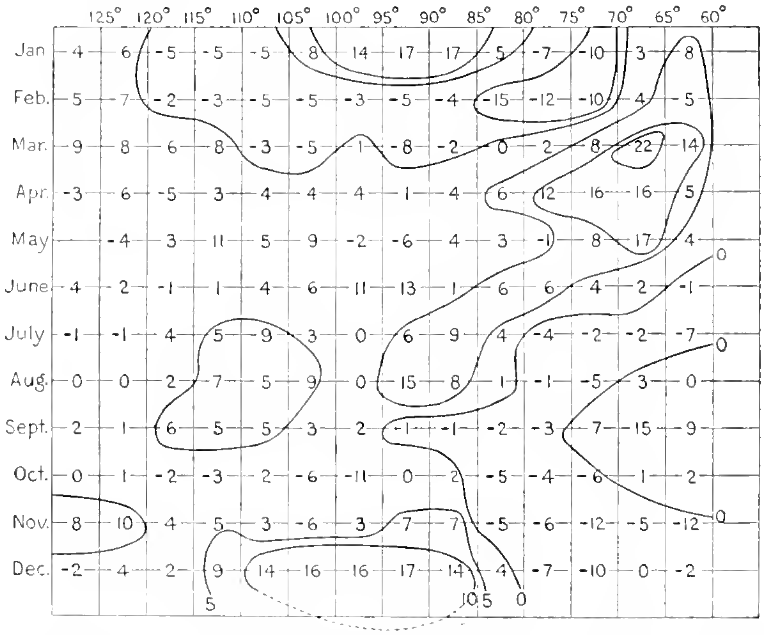


Fig. 68.—Changes in Storm Frequency by Months according to Longitude in Latitude 45° to 50°.

Finally, the last diagram, figure 71, presents a summary of the absolute differences in the number of recorded passages of storms during the earlier and later periods for each square of the map. The appearance of the map varies little, whether absolute differences are used, as in figure 71, or percentage differences. This map offers an interesting answer to the question whether the differences between the maps (as compiled by Dunwoody in the period from 1878 to 1887 and by myself for the period from 1899 to 1908) are due merely to differences in method and in observational material or to actual differences in the number of storms. On the map I have indicated the barometric stations in western Canada which were used for the earlier period: Fort Rae, Edmonton, Calgary, Medicine Hat, and Qu'Appelle. It will be seen that in the square where the greatest increase in storm frequency is noted there were three stations during the earlier period, which would seem to cover that region sufficiently. This renders strongly probable the conclusion that the increases and decreases shown in the various parts of the map are real—in great part at least. It is also noticeable that the eastern area of decreased frequency lies directly north of the area where the number of storms is greatest, which is what would be expected if the ideal storm track (that is, the mean of all tracks for a given period) had been shoved southward and westward. Concordant with this is the marked increase in frequency in the southwest and south. Taken as a whole it appears as if we had an area of increased storm frequency sweeping in a great arc from northwestern Canada down across the Rocky Mountain region to Denver and Texas, thence eastward through Louisiana, and up the Atlantic coast to Maine. This, it will be seen, is roughly parallel to the mean

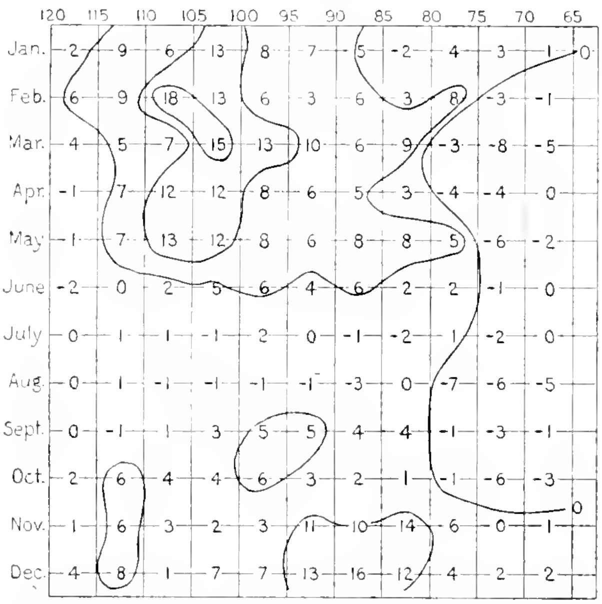


FIG. 69.—Changes in Storm Frequency by Months according to Longitude in Latitude 30–35°.

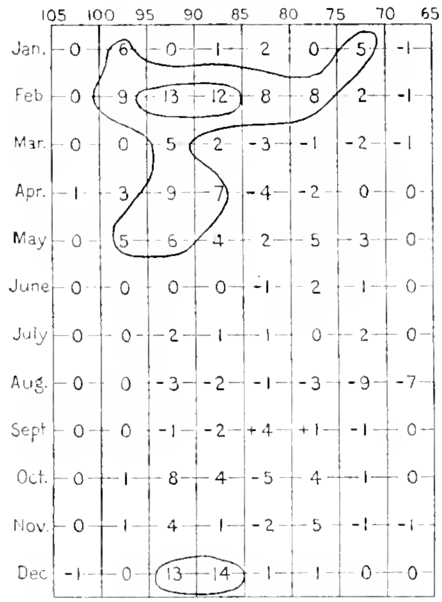


FIG. 70.—Changes in Storm Frequency by Months according to Longitude in Latitude 25–30°.

storm track as defined above, although much more curved than that, and lies in exactly the place where we should expect an increase if the track had been shoved southward.

In addition to the points already mentioned, there is another and wholly different aspect of the shift of the storm track to which attention should be called. The general

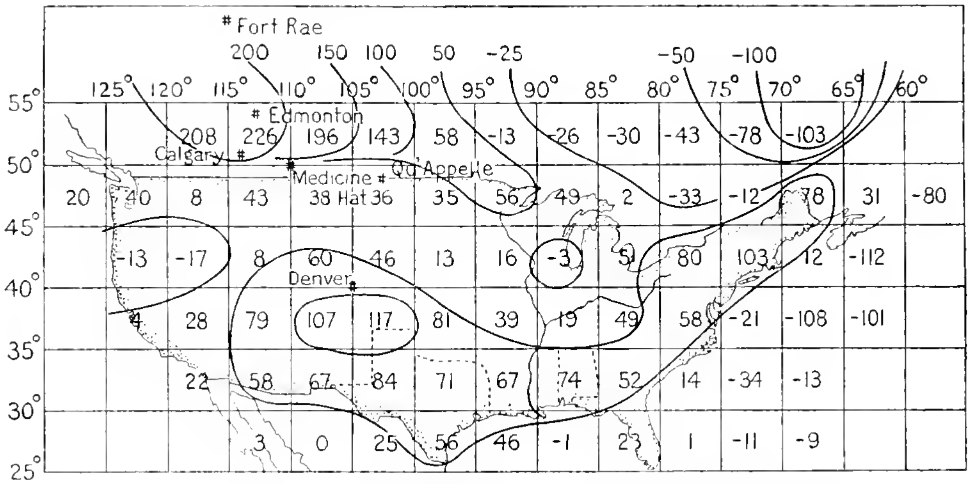


FIG. 71.—Summary of Differences in Storm Frequency, 1878–1887 and 1899–1908.

conclusion drawn from the maps seems to be that there has been a slight southerly and westerly shift of the storm track in the United States in the interval of twenty-one years. In this same interval the magnetic field in the United States has shown a similar shift. In discussing the mysterious changes in the secular variation during this period, Dr. L. A. Bauer says (Congressional Documents of the United States, vol. 5139, p. 217):

"The effect of these complicated changes * * * is to move the isogonic lines which lie east of the line of no change westward and those west of the no-annual-change-line eastward, or, in other words, the lines are being crowded together from both sides of the line of no change. This effect considered in company with the known changes in dip and intensity * * * implies that the magnetic pole has moved during the past twenty years chiefly southward, the west component of motion being greatly subordinate to the southerly one."

The hypothesis lies near that the storm track may center at the magnetic pole and may move with the magnetic field. If such an hypothesis can be entertained, the agreement here shown may be considered to be in harmony with it.

In conclusion, I should like to point to the desirability of having similar maps made for Japan and Europe, the only other areas of high storm frequency in the northern hemisphere. Lack of opportunity and the inaccessibility of the material have made it impossible to construct these maps, but they are necessary in order to give us a true insight into the shift of the storm track. In constructing such maps or in making others of the United States, it is particularly desirable that areas of less than 5° square should be employed, in order to bring out greater detail. Moreover, a single year should be the unit, and the maps for single years should be compared or combined by the use of overlapping means in such a way as to determine whether the location of storms varies from times of maximum to those of minimum sun-spots.*

This brings us to the end of Professor Kullmer's contribution. Its main significance lies in the fact that the average storm followed a course slightly farther south and west during the period from 1899 to 1908 than during the period from 1878 to 1887. To put the matter in another way, between the times of the two maps the zone of prevailing westerly storms moved very slightly equatorward from its earlier position. I would not be understood as magnifying the slight difference between the two maps. Doubtless conditions may soon once more become the same as they were during the period covered by Dunwoody's map, and there is no reason to suppose that any great change has taken place. The important point is that here we have direct evidence that the climatic zones of the world are at the present day subject to minor shiftings back and forth, and that these shiftings on a small scale produce the results which our assumed larger and more prolonged shiftings appear to have produced upon a really important scale. Meteorologists almost universally recognize the fact of such minor shiftings, but it is valuable to have the matter definitely recorded in maps which can readily be compared.

We have now seen that whether single years or longer periods such as decades be taken as our unit of time, the location of the storm tracks shows a tendency to vary. Let us now consider the same question, using a time unit of much greater length.

In discussing the changes of climate which appear to have taken place in Asia I have elsewhere shown that they appear to be of the same nature as those of the glacial period, the difference being one of degree, not kind. In the western hemisphere the evidence points to the same conclusion. Hence it will be of value to consider some of the latest results of researches upon the conditions of glaciation in polar regions at the present time. These results have been gathered into convenient form by Professor W. H. Hobbs, in his book upon "Glaciers," a volume which contains a large number of valuable facts as well as some suggestive theories. To meteorologists and glaciologists one of the surprising results of recent explorations of Greenland and the Antarctic continent has been the discovery that

* Since this chapter was in print, Professor Kullmer has constructed year maps of the storm frequency of the United States from 1874 to 1912, and of Europe from 1876 to 1891, the only period for which data are available. These maps are on the basis of areas 2.5° in latitude by 5° in longitude. They confirm the conclusions here set forth as to the shifting of the storm track, and also show that there is a distinct and unmistakable relation between the location and number of storms on the one hand and the number of sun-spots on the other. (See page 253.)

these ice-capped areas are regions of high rather than of low pressure. Previously it had been supposed that the general low pressure which appears to become more and more pronounced as one goes poleward prevails over all lands where continental ice-sheets now exist. It was thought that only in this way could sufficient precipitation be obtained to support the great ice-fields and send out the thousands of bergs and floes which wreck our ships.

As soon as explorers began to study the winds of ice-capped regions with any care, however, they discovered that the prevailing movement of the air is strongly outward. At times it may be reversed, but not for long. This means, apparently, that high barometric pressure prevails in the interior and is busily forcing the air outward except at times when some general disturbance upsets the normal conditions. This is what would naturally be expected, since vast areas of snow are bound to be extremely cold and hence are likely to induce high barometric pressure. Hitherto, however, it has generally been supposed that such almost continuous high pressure could not characterize these regions because there would be no way of obtaining precipitation. Hobbs has attempted to explain this by an ingenious hypothesis which holds that, under the peculiar conditions of glaciation and of the newly discovered inversion of atmospheric temperature at high levels, fine crystals of snow can be deposited even when the barometer is high and the upper air clear. Whether his theory is sound or not can not here be discussed, but it seems at least to be worthy of careful consideration. Its chief value, however, lies in its emphasis of the fact that regions of continental glaciation appear to be areas of high pressure. This being so, an increase in the area of continental glaciation would mean an increase in the area of permanent high pressure. At the height of a glacial epoch high pressure would prevail throughout the year over most of the northeastern part of North America, and over northwestern Europe. If other conditions remained in general the same as at present, the barometric gradients from the great glaciated areas of high pressure to the low areas of the oceans and of equatorial regions would be steeper than now. Hence the winds would acquire great strength, storms would be more numerous than now, and they would follow more southerly courses. Forced far to the south by the great continental high areas both in northeastern America and northwestern Europe, they would probably swing down into the Gulf of Mexico or the Sahara Desert, as the case might be, and the climates of those southerly regions would partake of the unstable and stimulating nature which to-day is so characteristic of the parts of North America and Europe where the world's most progressive races dwell.

If we are right in supposing that the climatic changes of which we seem to have found evidence during historic times are of the same nature as those of the glacial period, we can readily see how in the days of Yucatan's glory the storminess now characteristic of the United States may have prevailed farther south. At all seasons, but especially during the winter, cyclonic disturbances were probably more frequent and severe than now, the winds presumably blew more forcibly, and the minimum temperature of Yucatan may have fallen as low as freezing instead of only to 50°. The effect which such a southward shifting of the stormy belt would have upon precipitation deserves careful consideration. At present the "northers" bring very little rain to Yucatan, since they are cold winds moving rapidly toward warmer regions. Therefore their capacity for moisture increases and they are not likely to produce much rain. Neither their frequent prevalence nor the general shoving southward of the dry subtropical zone would probably have much effect upon the winter rainfall of the dry northern parts of Yucatan, but might much diminish that of the forested regions. This is because the winter rainfall is here due to the trade winds. If cyclonic storms came farther south than at present, they would destroy the trade winds in this latitude and would allow them to prevail only in regions farther south. Hence there would not be any steady winds blowing in from the sea through the winter and causing abundant precipitation. This would give rise to a dry season longer and more intense than that which now prevails there and would thus tend to cause jungle to take the place of forests.

The effect of such a change upon the summer rains, on the other hand, can not easily be determined. Possibly the general strengthening of the winds would bring the equatorial rains farther north than is now the case, or would at least make them more abundant. It is equally possible that the shoving southward of the zone of storms would be as prominent a feature in summer as in winter, and hence that the equatorial rains would not come so far north as at present. A possible test of this matter lies in a comparison of the curve of the sequoia in California with the fluctuations of the lakes around the City of Mexico, but the data are so imperfect that it is not conclusive. The California growth represents the variations in a purely winter type of rainfall characteristic of the zone of prevailing westerlies. The fluctuations of the lakes of Mexico, on the other hand, are due to a rainfall which comes almost entirely, but not wholly, from May to October, and is largely of the equatorial type. Hence, if a strengthening of the earth's circulation increases the equatorial rains as well as those of the zone of westerlies, we should expect to find the Mexican lakes high at the same time when the California trees grow rapidly. This would not necessarily mean that in summer the rains of the equatorial type shifted farther north than now, although this is a possibility. It would merely indicate that the more rapid circulation of the air caused the equatorial rains to be heavier than at present.

With this in mind let us sum up the variations of the lakes, as set forth in Chapter X, and compare them with the curve of the sequoia as given in figure 72. Our first knowledge of the Mexican lake suggests that in 1325 A. D., when the Aztecs founded the City of Mexico, it stood quite high. At this time the California trees were growing very rapidly and grew still more rapidly during the succeeding decade. Then their growth decreased until about 1420. Thereafter, for the space of forty years, the growth of the trees remained practically stationary—or, to put it in another way, a climatic change markedly checked a previously rapid rate of decline, but did not succeed in reversing it. Just what happened in Mexico at this time we do not know. It merely appears that during the forty years of the change in California, conditions were such that after some severe floods in the early years of the reign of Montezuma, the Aztecs were at length led to build the first dike in 1446. The history of the inundations of Mexico City from the time of Montezuma to 1800 A. D. is summed up in table 10. The data here used are taken partly from Humboldt, who speaks of fourteen chief floods between the time of Montezuma and his own day. The chief of these, which occurred in 1553, 1604, and 1607, are mentioned (it will be remembered) by Torquemada. Certain other floods are mentioned by Cavo,* whose work terminates with the year 1765. From this work Mr. A. F. Bandelier has kindly gleaned for me the references noted in the table. The inundations mentioned only by Cavo are less important than those mentioned by the other authorities.

The table scarcely requires explanation, but a few words as to the general course of events may not be amiss. After the time of Montezuma the growth of the trees fell off at a very rapid rate, and from about 1460 to 1490 we find them growing as slowly as at any known period. No inundations are recorded during this time, but Humboldt tells us that the Mexican lakes fell to so low a level that the city suffered much distress because canoes laden with food could not come in as formerly from the surrounding country. Thereafter the rate of growth of the trees increased rapidly until about 1560, and in this period we find four inundations, the last of which, in 1553, was famous. It is noteworthy that it occurred at about the time when the trees reached their maximum rate of growth. Next the trees fell off slightly for thirty years, approximately from 1565 to 1595, and Mexico City did not suffer greatly, although one inundation of no great note occurred in 1580. Then the growth of the trees increased at a very rapid rate during the decade from 1600

* Les Tres Siglos de Mejico (Jalapa, 1870, edited by Carlos Maria de Bustamentes).

to 1610, and at this same time Mexico suffered from two phenomenal inundations. Thereafter there came a brief dry period in Mexico marked by drought and famine in 1608 and again in 1615. This does not appear in the California trees, whose growth merely ceases to increase in rate, but still remains high. It is quite possible, however, that these particular years were bad years in California, but that their effect is concealed by the good

TABLE 10.

Year.	Authority.	Conditions in Mexico City.	Conditions of tree growth in California.	Relation of Mexican lakes and California trees.
1440(?)	Torquemada; Humboldt.	Great inundation	Slight decrease in rate of growth compared with previous decade, but during this general period a very great decrease changes to essential uniformity.	Neutral.
1498	Humboldt	Inundation. This has no great significance, because it was due to the mistaken policy of turning the Huitzilopoche River into Lake Tezcuco.	Slow, but steadily increasing	Agreement.
1519	Do	Inundation	Medium in amount and rapidly increasing.	Do.
1523	Cavo, p. 25	Do	Medium and only slightly increasing	Neutral.
1553	Humboldt; Torquemada; Cavo, p. 109.	A famous inundation. According to Cavo a drought was broken by a violent rain that lasted not quite 24 hours and inundated the whole valley of Mexico. Such inundations (according to Bandelier) were at that time frequent and were not regularly recorded on account of being looked upon as a common occurrence.	Rapid with great increase	Marked agreement
1580	Humboldt	Inundation	Medium with moderate decrease.	Disagreement.
1604	Do; Torquemada.	Famous inundation	Rapid growth and great increase.	Marked agreement.
1607	Humboldt; Torquemada; Cavo, p. 162.	Great inundation	Do	Do.
1623	Cavo, p. 175	Inundation in December	Rapid, but beginning to decrease	Neutral.
1629	Humboldt; Cavo, p. 183.	Inundation. Great rains	Do	Do.
1645	Cavo, p. 196	Inundation	Medium, but with slight increase	Do.
1648	Humboldt	Do	Do	Do.
1675	Do	Do	Rapid and increasing	Agreement.
1691	Cavo, p. 233	Inundation and also heavy frosts unusually early.	This decade was characterized by marked decrease, but at its beginning the growth was very rapid, so that it is impossible to determine whether the first year of the decade was characterized by slow growth or fast.	Neutral.
1697	Cavo, p. 240	Inundation	Same as preceding, but as this year comes toward the end of the decade it probably should be counted as distinct disagreement.	Disagreement.
1707	Humboldt	Do	Slow with rapid decrease	Pronounced disagreement.
1732	Do	Do	Moderately rapid, and with rapid increase.	Agreement.
1748	Do	Do	Rapid with marked increase	Pronounced agreement.
1762	Cavo, p. 293	Overflow of Lake of Mexico	Fairly high, but rapidly decreasing. This case may be like that of 1691, but it is better to reckon it as disagreement.	Disagreement.
1772	Humboldt	Inundation	Low but with a distinct rise	Agreement.
1795	Do	Do	Moderately rapid with great increase	Do.

The following occurrences of dry times should be mentioned in connection with the table: Cavo (p. 109) states that the violent floods of 1553 followed a drought, but it is not evident whether the drought was of any importance. In 1608 (p. 164) after the great floods of 1604 and 1607, he speaks of another drought followed by the receding of the lake in 1609, while in 1615 (p. 171) he records a drought and famine. Both of these must be regarded as distinct disagreements. In 1750 (p. 287) he records famines in northern Mexico, but good crops south of Guanajuato. This comes at the end of a time of rapidly increasing growth in the trees, but is not distinct enough to be counted, except as neutral.

years before and after them. In the next decade, 1621 to 1630, we find the trees still growing rapidly, and in Mexico City there were two inundations. Thereafter the trees decline, but only a little. In the decade from 1641 to 1650 their growth revives very slightly, and in Mexico there were two inundations, neither of them of the first importance.

In table 10 these cases are marked as neutral, but in reality it might be fair to mark them as showing agreement. The next event in the history of the trees is an increase in the rate of growth lasting for thirty years. During this period a tunnel carried off the surplus waters of the lakes, and therefore no inundations are recorded, even though it is possible that some would otherwise have occurred. In 1675, at the time when the rate of growth of the trees was increasing most rapidly, a flood is said to have so injured the tunnel

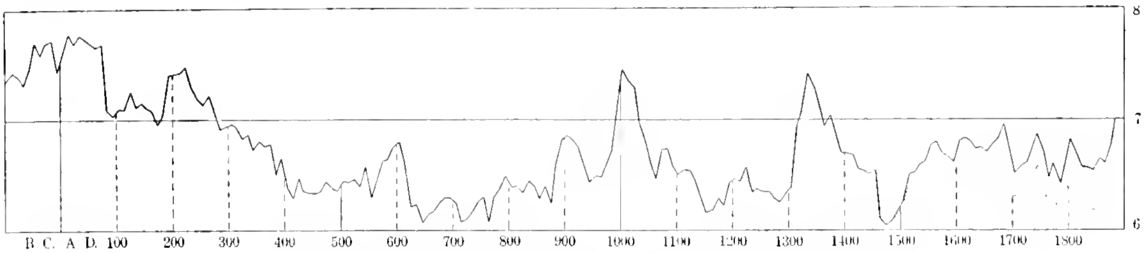


FIG. 72.—Changes of Climate in California for 2,000 Years.

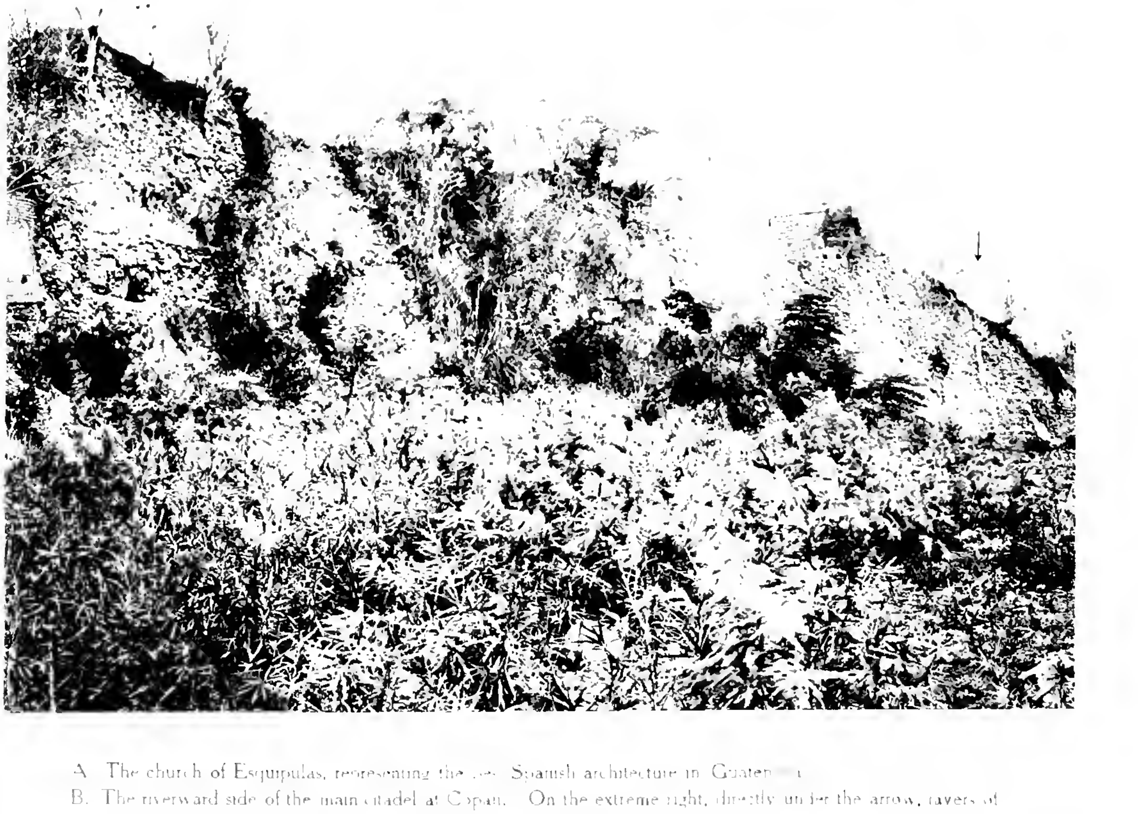
This figure is the same as the part of figure 50 after 100 B. C., but is plotted with a threefold greater vertical scale.

that it caved in. Nevertheless, Mexico City was not flooded, probably because even after the collapse of the tunnel it still functioned. In 1697 and again in 1707 two inundations occurred, which are markedly out of harmony with the apparent rainfall in California. About 1730 the trees again rapidly increased their rate of growth, and Mexico suffered from two inundations. It is probable that a somewhat general increase of rainfall stimulated the Mexicans once more to attempt to get rid of the water, for in 1755 a long series of schemes for draining the lakes culminated in a really successful tunnel. After this time the increasing number of artificial constructions makes it impossible to judge of the climate from the fluctuations of the lakes. Of the three inundations recorded between 1750 and 1800 the first occurred in a decade when the trees showed a marked decrease in growth, whereas the other two occurred at a time when the trees increased their rate of growth.

To sum up the matter we find records of twenty inundations, great and small, between the times of Montezuma and Humboldt. All the great inundations took place at times when the trees were growing rapidly. Including great and small, we find four cases where there is a disagreement between the trees and the lakes, seven in which the matter is open to question (since the data for individual years are not available for comparison), and ten showing agreement. The suggestive point about the whole matter is that, in spite of minor disagreements, the main eras of high water in the lakes seem to correspond with periods of rapid or increasing growth in the trees. So far as this single line of evidence is concerned, it seems to suggest that when the *winter* rainfall increases in the zone of prevailing westerlies, the *summer* rainfall increases on the borders of the equatorial zone. It must be remembered, however, that in some cases, such as 1623, the floods were due to winter rainfall, suggesting that winter storms came farther south than usual. If the conclusion here reached is really true, it appears that at certain past periods not only Mexico City but such places as Yucatan probably had more summer rain than at present, while during the winter not only did all parts of the country enjoy greater variations of temperature than is now the case, but the parts now receiving rains from the trade-winds were drier than to-day, and hence were covered with jungle and bush instead of forest and jungle.

How great a direct effect upon the inhabitants may have been produced by these inferred climatic changes it is hard to tell. In a later volume I hope to discuss this question fully and to present the results of a large series of observations upon the state of human activity under widely different climatic conditions. The results there to be given will be based upon absolute mathematical measurements of human efficiency. At present, however, we must be content with a single example which illustrates one of the important ways in which climatic variations may produce their effects. During my visit to Yucatan I again and again inquired of all sorts of people as to the kind of weather when the modern Yucatecos work most vigorously. The universal answer was on "fresh" days, which means the coolest days that Yucatan ever enjoys. When I put this question to Mr. E. H. Thompson he answered it as did every one else, and then with characteristic energy went out early the next morning to interview some of the best-informed men among the Indians. They, too, gave the usual answer, and then, thinking it over a little more, added, "Yes, the Mayas work hardest when there is a fresh spell; the morning after a 'norther' is the time; then the air is cool and clear, and the women bake the tortillas much more quickly than usual, so that we get away to work early." Nothing for to-day, as we have said, is ever prepared yesterday in Yucatan, and so in the morning the men always have to wait until the women have ground some corn, mixed the batter, and cooked some thin tortillas on a flat sheet of iron. Therefore the husbands, not being able to depart until the day's supply of bread is ready, take especial note of the speed with which it is prepared. Perhaps this may seem a trivial thing to mention in connection with a great problem like that of the cause of the rise and fall of nations, but it illustrates the fact that among the physical stimuli which may control human efficiency none is more potent than climate. Perchance, if Yucatan had a norther every three days instead of only at rare intervals, the energy of the population might be greatly increased. If the northers were so cold that the temperature fell to freezing, as it does at Canton in China, scarcely farther from the equator than is Yucatan, the present Yucatecos might in time become as efficient as the Cantonese. With our present scanty knowledge of the exact effects of varying conditions of temperature, pressure, humidity, and the like upon man's vital processes, it would be rash to say how far the difference between the Yucatan of the past and that of the present may be due in part to climatic causes. This much, however, can be safely said: if the shifting of zones has taken place in any such way as we have inferred, the peculiar contrast between the wonderfully progressive people who once dwelt in Yucatan and the indolent present inhabitants is much less inexplicable than is now the case.

A


B


A The church of Esquipulas, representing the ... Spanish architecture in Guatemala.
B. The riverward side of the main citadel at Copan. On the extreme right, directly under the arrow, layers of alluvial deposits can be seen underlying artificial constructions. The wall of figure 73 lies on the extreme left.

CHAPTER XVII.

GUATEMALA AND THE HIGHEST NATIVE AMERICAN CIVILIZATION.*

When the final revision of this volume was made in January and February 1913, the author felt that his conclusions as to the torrid zone required further testing. The logical place for such a test was Guatemala, since there the Mayas brought to a culmination the highest civilization of native American origin. Accordingly in March and April 1913, independently of the Carnegie Institution, he spent about four weeks in that country or on its borders in British and Spanish Honduras. In previous chapters four chief lines of evidence have been used, namely, alluvial terraces, changes in lakes, the distribution of ruins, and the rate of growth of trees. Only two of these, terraces and ruins, are of much significance in Guatemala. Lakes, to be sure, are numerous, and of great beauty, but all have outlets, and are of interest chiefly in relation to the volcanoes which seem in several cases to have formed them by closing deep valleys which previously opened toward the Pacific. The trees of Guatemala are of course abundant, but are of little use for our purpose. Those growing in the tropical forests of the lowlands are often of large size and perhaps of considerable age, but constant moisture renders their rings too indefinite to be reliable. The pines of the highlands, on the other hand, although possessed of definite annual rings because of the pronounced contrast between the wet and dry seasons, appear rarely to be over 100 years old, and hence are of little importance. Terraces and ruins, on the other hand, are not only abundant, but they fortunately lie sometimes in intimate juxtaposition.

Our consideration of the terraces and ruins will be clearer if preceded by a brief description of the country as a whole.† From northeast to southwest, Guatemala, together with British Honduras, which for convenience I shall treat as if it were part of the same country, consists of a young Atlantic plain, a system of mature mountains, a young volcanic plateau, and a young Pacific plain. The Atlantic plain is merely a continuation of that of Mexico, which, after expanding into the peninsula of Yucatan, diminishes in width until it is finally drowned beneath the sea east of the Cockscomb Mountains of southern British Honduras. The whole plain is densely forested, intensely fever-stricken, and almost uninhabited. A few mahogany cutters form villages along its winding rivers, a small number of cattle are fattened in grassy savannas where an excess of sand or water prevents the growth of trees, and a few primitive Indians cultivate isolated patches of land here and there in its remote recesses. As a whole it is one of the world's most scantily populated and least-known districts.

The mature mountains consist of a series of ranges of distorted strata running nearly east and west and rising from 5,000 to 10,000 feet above the sea. Their seaward portions, where exposed to the northeast trades, are heavily forested and feverish, and therefore almost uninhabited. The higher portions, and also those of the lower mountains which are not kept continually wet by the trade winds, are covered with pines and support a moderate number of people. Most of the population, however, is concentrated in deep, dry valleys or basins such as those of Coban and Zacapa, which lie among the mountains and are thus protected from excessive moisture.

* This chapter, in a somewhat changed form, is reprinted from the Transactions of the American Philosophical Society, vol. LII, No. 211, pp. 467–487, Philadelphia, 1913.

† See map, p. 174.

At their western end the old mountain ranges are buried under vast deposits of volcanic tuff forming a broad plateau. On the western border of this a line of splendid volcanoes, 10,000 to 13,500 feet high, extends along the Pacific side of the country at a distance of 30 to 40 miles from the coast. The plateau itself, at an altitude of from 5,000 to 8,000 feet above the sea, is relatively flat, although divided, as it were, into terraces at various elevations. It would be easy to traverse except that it is frequently cut by deep "barancos" or canyons with nearly vertical sides. In a state of nature most of the plateau would be covered with an open, grassy pine forest, but its healthfulness and coolness have caused it to be almost entirely cleared and to be the home of one of the densest agricultural populations to be found in any part of the world.

Southwest of the plateau the lower slopes of the volcanoes are densely forested and feverish, for rain falls whenever the trade-winds weaken and a movement of the air takes place from the Pacific. Coffee is here raised on a large scale, but were it not for this the population would be relatively scarce. The lower edge of the coffee country extends into the Pacific plain. While the volcanoes were building up the plateau, the rivers were busily carrying volcanic materials down toward the Pacific Ocean, and forming a smooth piedmont plain 20 to 30 miles wide. The inner edge of the plain lies in the zone of dense jungle, 500 to 1,000 feet above the sea. The seaward edge is relatively dry and bears a wearisome growth of thick bushes. Everywhere the plain is unhealthful and sparsely populated, for in the rainy seasons its flat surface holds the water in stagnant swamps, where mosquitoes breed by the million.

Turning now to the terraces, our first line of evidence as to changes of climate, we find an interesting contrast between the Pacific and Atlantic slopes. On the Pacific slope I saw more or less of at least a dozen small river systems, some in their head-waters before they had passed through the great line of volcanoes, and some farther downstream. None are well terraced like certain valleys in southern Mexico, but many show evidence that a terracing process has not been wholly absent. On the river between Tecpam and Gaudines, for instance, the valley was first eroded to nearly its present level, was then filled to a depth of at least 30 to 40 feet with coarse alluvium, and has since been re-excavated. Before the re-excavation the stream was displaced to one side of the valley, so that when it began cutting downward it soon encountered solid rock. In this it has cut only a narrow gorge, although both upstream and down it has so broadened the valley floor that only faint traces of terraces are seen. Many other phenomena indicate that as a rule the valleys of the Pacific slope have recently experienced two periods of terracing and that the terraces occur both above and below the volcanoes, but are generally better developed above. As might be anticipated, however, the evidence is not strong, partly because the streams fall rapidly and the slopes are well covered with vegetation, and still more because where volcanoes have been active so recently it would be idle to look for marked climatic terraces of any great age. If the scanty terraces now visible are of climatic rather than volcanic origin, they may enable us to date various events in the volcanic history of the country. For our present purpose, however, they possess no special importance.

On the Atlantic slope the case is far different, for volcanic action either ceased long ago or never prevailed, and large areas are so dry that almost any climatic change would have an appreciable effect upon vegetation. I was able to see only two drainage systems, those of the large Motagua River and the small Santa Toma just north of it. They suffice, however, to show that here, just as in southern Mexico, Arizona, Persia, and many other places, the most recent geological times have been characterized by at least four terrace-making epochs. The reasons for believing the terraces to be of climatic rather than of tectonic origin are the same here as elsewhere. The very fact of their occurrence here with the same character as in far-distant regions is in itself a strong reason for assigning to them an origin of world-wide application, such as climate, rather than local earth-movements. On the lower Motagua River, in the wet forested country, the terraces are only slightly developed, but may be seen near the notable ruins of Quirigua and elsewhere; on the dry middle course of the river, from Zacapa upward, they are highly developed; and in the moderately watered regions of the upper course they are also well developed. This is likewise the case along the only two main tributaries which I saw, the Copan and Chiquimula branches, which join the main river at Zacapa. On the upper river, where it is crossed by the road from S. Toma de Chichestenango to S. Cruz de Quiché, there is convincing proof that the terrace-making process consisted of both erosion and deposition. Because of the change in the relative positions of the main stream and a tributary, one can see an old channel which was first excavated and then filled with gravel to a depth of 40 to 50 feet and perhaps more. The top of this gravel corresponds with a well-developed terrace.

The Motagua River, flowing from high, dry regions through alternate gorges and broad valleys, is the kind of stream that might be expected to have terraces of climatic origin. Its little neighbor, the Santa Toma, on the other hand, is of quite a different nature. It is a short, insignificant stream running down from the eastern end of the Sierra de las Minas, between the large Motagua River on the south and the Rio Dolce on the north. Its entire course appears from the maps to be not over 30 miles, and all of it apparently lies among dense vegetation. In this region, in contrast with the youthful coastal plain of Yucatan, the last main movement of the land seems to have been downward, so that the inner corner of the Gulf of Honduras, near Puerto Barrios and Livingstone, presents a strikingly bold, indented coast line with isolated islands and deep inlets. This movement, however, occurred long ago and since its completion a long period of comparative stability has allowed large deltas to be formed. In ascending the Santa Toma River one traverses a delta for perhaps 5 miles, first through mangrove swamps and then through the ordinary, dense tropical forest. A small terrace appears after one is well within the solid portion of the delta; farther inland it becomes higher, and where the delta joins the hilly old land at least four terraces are well developed. The full development of the delta and the apparent absence of any signs of recent upheaval of the land agree with the lines of evidence already cited in other chapters in indicating a climatic rather than tectonic origin of the terraces. If this be correct, the terraces of the Santa Toma are particularly significant because the whole course of the river lies in a region of abundant vegetation. This suggests that in tropical regions, unlike those of the temperate zone, changes of climate have appreciably influenced the amount of vegetation, or at least the rate of erosion, not only in arid regions but even where dense forests prevail.

If the terraces are really of climatic origin important consequences follow when we investigate their relation to ruins. Among the greatest of the ruins of Maya land are those of Copan on the Copan tributary of the Motagua, just over the Guatemalan border in northern Honduras. Beginning at the wretched little modern village of Copan, the ruins extend up the right bank of the river for at least 1.5 miles, and in the last three-quarters of a mile of that distance the ancient walls are practically continuous. At the southwestern end of the main ruins the walls of the chief citadel, or temple, rise directly from the river, which is almost undermining them and may soon cause their fall. The relation of the wall to the deposits of the river is shown in the profile and cross-section of figure 73, and in the accompanying description. It is also illustrated in Plate 10, B, page 211.

Before the full meaning of the diagram is explained, attention should be called to figure 74. From this it will be seen that the ruins stand upon a terrace about 18 feet above the present low-water level. They follow this very closely and were evidently built along it. Just below it there lies another terrace, 12 feet above low-water level, and to-day quite as good a place for houses as is the upper terrace. The fact that no trace of ruins is found upon it and the conditions of deposition shown in figure 73 seem to indicate that when

Copan was an inhabited city the edge of the 18-foot terrace was washed by the river. To-day floods sometimes reach the foot of the 12-foot terrace, but never rise higher. If the river should again proceed to deepen its channel the present flood-plain would in turn become a third terrace, but there seems to be no such tendency. It should be added that above the 18-foot terrace are traces of others of much greater age, but these do not concern us.

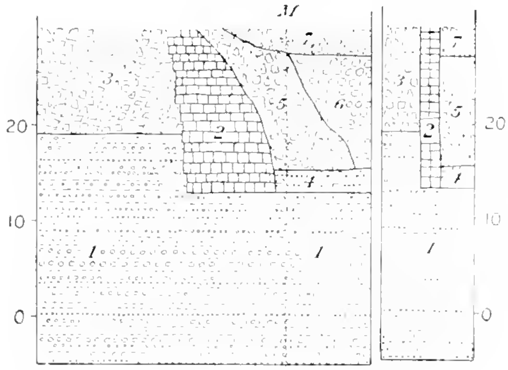


Fig. 73.—Diagrammatic Sections of Wall and Deposits at Copan Ruins.

A. Oblique section as seen from river.
B. Cross-section along M–N.

KEY TO FIGURE 73.

1. = Original river deposits on which the ancient town of Copan was built Upper parts with some clay and fine gravel, but mostly coarse cobbles with small bands of finer gravel. The upper cobble layers are in a matrix of more clayey material and look as if they had been laid down to a depth of 5 to 6 feet, under somewhat unusual conditions, *e. g.*, as if the ordinary course of the river had been interfered with by man. The top of this deposit is about 18 to 19 feet above present low-water level, and 11 to 12 feet above present high-water level.
2. = Masonry wall extending down 6 to 7 feet below top of (1), apparently to low-water level of the period when it was built. Otherwise the wall must have been laid in a trench, which is improbable because of the even stratification of (4).
3. = Rubble filling, placed inside of wall to form the great mound on which the temple is built.
4. = Fine alluvial materials such as fine water-laid gravel and sand mixed with some layers of rounded cobbles and also with layers containing angular bits of limestone, broken cherty flint, and also larger blocks of the limestone of which the walls are made. This looks like a deposit laid down in water just after the wall was built. It lies outside of (2), just as (2) lies outside of (I) and (3), and it lies on (1) and seems to coalesce with it. Its top is about 4 feet below that of (1). The relative ages of (3) and (4) are not evident.
5. = Broken rubble from the ruins up above. It lies outside of (2) and above (4). It is like (3), only more irregular and with less cobblestones, probably because it fell from the high parts of the wall.
6. = About 10 feet of even layers of cobbles laid down by man in a reddish clayey matrix. No significance.
7. = Grayish rubble. No significance.

The facts which have just been stated, and which are illustrated in figures 73 and 74, seem to indicate that the history of the Copan River in relation to the ruins has been approximately as follows: The earliest of the finely carved stelæ at Copan bears a date which Morley reads as 251 A.D., but which Bowditch puts about 250 years earlier. The lowest walls of the main temple or citadel must quite surely have been built before the stelæ were carved, and it seems safe to say that they probably date back before the time of Christ. Previous to that date the river had built up its flood-plain approximately to the present 18-foot level. At that time, however, it probably was not aggrading its flood-plain to any great extent, for in that case the town would frequently have been flooded. Nevertheless, it may sometimes have overflowed into the town, and to this may be due the somewhat disturbed stratification of the upper part of deposit No. 1 in figure 73, a deposit which lies inside the wall and corresponds with the general upper layer of the 18-foot terrace. Even if this is not the case, the river rose quite high, for on the outside of the wall it deposited materials (No. 4 in figure 73) within 4 feet of the level of the main terrace. Next the river cut down its channel to an unknown depth below the 18-foot terrace. Then it built up its flood-plain, perhaps much, perhaps very little, and formed the present 12-foot level. Next it again cut downward, and then once more laid down deposits to form the present flood-plain.

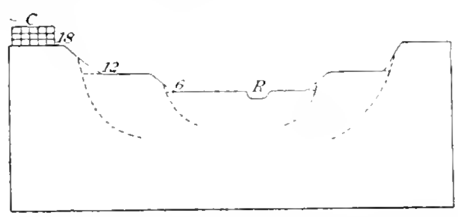


Fig. 74.—Relation of Terraces and Ruins at Copan.

Numerals indicate approximate height above low-water level. R = River. C = Ruined walls of Copan.

How markedly the processes of degradation and aggradation were separated we have as yet no knowledge, but on the upper Motagua and in most of the other parts of the world where such terraces are seen the separation is usually distinct. If we assume that the same is true here, and if we further assume the correctness of our previous conclusions as to the synchronism of wet times in California and dry times in Central America, we may frame the following tentative table on the basis of the curve of growth of the sequoias:

(1) Previous to 100 B.C. Period of aggradation and presumably of increasing aridity antecedent to the building of Copan.
(2) 100 B.C.–250 A.D. Period of high river-level, but not of much change of level in flood-plain, that is, a time when, although aridity was no longer increasing, there was no special tendency toward more moisture. Building of Copan.
(3) 250–700 A.D. Period of degradation or downcutting by the river up to the edge of the 18-foot terrace—that is, a time when the amount of rain and of vegetation was increasing. Occupation of Copan followed by decline and abandonment. The date of the last monument is about 500 A.D. according to Spinden and 230 A.D. according to Bowditch.
(4) 700–1000 A.D. Period of aggradation and of increasing aridity during which the river built up its flood-plain to the 12-foot level.
(5) 1000–1300 A.D. Period of degradation and of increasing moisture with deepening of river channel in such a way as to form the 12-foot terrace.
(6) 1300–1900 A.D. Period of minor fluctuations of climate with alternate deposition and erosion, the present flood-plain being approximately the mean level.

In a table such as this the possibility of error is great, for the number of unknown factors is large and many assumptions must of necessity be made. I do not present it as in any way final, or as more than a mere suggestion of the way in which, when far fuller information is available, we may perhaps be able to correlate such diverse phenomena as changes of climate, variations in the activity of rivers, and events of history. Its present importance lies in the fact that when we submit our climatic theories to the severe test of a comparison between the growth of trees in California and the activity of rivers in Guatemala, we at least find no obvious contradiction.

Leaving, now, this rather speculative matter, we may briefly sum up the evidence of the terraces. Two points stand out clearly:

(1) There can be no question that in Guatemala we find terraces of the kind that our climatic theory would lead us to expect. The only surprising thing is that they occur in places where the vegetation is denser than we should have anticipated, which suggests that if climatic changes have occurred, they have affected vegetation in moist tropical regions more than in moist temperate regions.

(2) The terrace-making process has been active since the foundation of Copan, one of the chief of the ancient Maya towns, but the activity has been mild compared with that of earlier times. If the tectonic theory of alluvial terraces is correct, these two points have no special significance. If the climatic theory is correct, they add much to the reliability of our main conclusions.

We come now to a subject much more significant than the terraces. In Guatemala the former distribution of population and still more of culture was utterly different from that of to-day. Almost nowhere else in the whole world have 2,000 years or less produced so profound a change as in this little country of only about 48,000 square miles. The normal decay of races, the interplay of historic forces, the invasion of barbarians, the decadence due to luxury, vice, and irreligion, the change of the center of world power, each or all of these causes, or any others usually appealed to by historians, can not explain the matter. The question is not why the Maya civilization arose, nor why it fell. We may assume that it arose because it is the nature of a young and vigorous race to make progress, and that it fell because it is the nature of an old and exhausted civilization to decay. The assumption does not help us in the least, for it does not touch our problem. To-day the most progressive and energetic people of Guatemala, its densest population, its greatest towns, its center of wealth, learning, and culture, so far as these things exist, are all located in the relatively open, healthful, easily accessible and easily tillable highlands; in the past these same things were located in the most inaccessible, unhealthful, and untillable low lands. Why the change?

From the point of view of present habitability Guatemala, together with British Honduras, is divided into three main belts dependent on vegetation—the Atlantic forest, the central dry land, and the Pacific forest. Each of these in turn may be divided into two parts. The plain of British Honduras in the north to a width of 50 miles, and the mountains of the southern part of that country and of eastern Guatemala to a distance of perhaps 30 miles from the coast form the first division of the Atlantic forest. Showers at all seasons, either from the trade winds in winter or from the subequatorial area of low pressure in summer, cause the land to be covered with a dense tropical forest and to be infested with malignant types of malarial fevers. Only on the coast are there any real towns, and they exist chiefly by grace of the trade winds, which blow freshly from the ocean and drive away the mosquitoes. Strung along the beach, under the cocoanut palms, the low whitewashed houses of these towns make quite a show from the sea, but back of the first row there is often nothing but deadly swamp and mosquitoes. In the interior a few little villages sit in clearings by the brink of the somber rivers, and wait in sun or rain for precious mahogany logs to be hauled or floated out of the interior. Save for these few people no one inhabits the dense forests. If the coast towns and the mahogany-cutters be excluded, the whole region can not boast a population of much more than one person to every 10 square miles, while even if the towns and woodcutters be included, British Honduras with an area of 7,500 square miles has only 42,000 people, or less than 6 to the square mile. The forests and fevers now keep mankind away, and apparently much the same was true in the past, for we find here only a few widely scattered ruins.

Inland from the coast strip there lies another section of the Atlantic forest, occupying most of the almost unexplored and semi-independent Guatemalan province of Peten, and extending south past Quirigua towards Copan. In the north this Peten strip is a plain from which rise a few low ridges running east and west and having a height of 1,000 feet more or less. In the south it becomes mountainous. The vegetation is almost as dense as that of the coast strip, except that in Peten considerable areas of grassy savanna prevail, thin pine forests grow in the sandy tracts known as "pine ridges," and on the westward edge and in other favored spots—among which Flores on Lake Peten is the chief—the forest breaks down into jungle. The savannas, as already suggested, are due either to an excess of water, often held near the surface by clayey hardpan, or to sand. The pine ridges, which are not ridges but merely slight swellings in the plain, are due to accumulations of sand. Neither in the past nor at present does it ever appear to have been possible to cultivate either the savannas or the pine ridges, but since the introduction of cattle by the Spaniards, they have been utilized somewhat for pasturage. They possess not only the advantage of being fit for cattle-raising, but of being relatively healthful, and of being bordered by narrow strips of jungle wherein primitive agriculture is possible. In the more extensive jungle regions on the borders of the Peten strip a few villages are located, among which Copan is most worthy of mention. Aside from the limited areas of savannas, pine ridges, and jungle, the country is covered with forest, and is so feverish and so difficult to cultivate that its only inhabitants are mahogany-cutters, gatherers of chicle gum, or raisers of bananas for export. All of these occupations, together with cattle-raising, are due entirely to the influence of modern European civilization, and had no place in the pre-Columbian period. The banana plantations have grown up within a few years and are practically all the work of the United Fruit Company, which employs over 4,000 people in the valley of the Motagua River. Only some powerful stimulus, like the demand of the United States for fruit, could cause such plantations to arise; the strictest supervision is necessary in order that the bushes may be cut every three months, for in a year the native vegetation grows 10 feet or so, and if left to itself would soon choke the banana plants. Still more unremitting vigilance is necessary to keep both the white men and the natives in health. From the wages of every employee, whether he receive 50 cents or 50 dollars per day, the company takes 2 per cent to pay for sanitary measures. Every plantation has its doctor and dispensary, and natives and foreigners alike are continually dosed with quinine. Yet even so, at certain seasons of the year, a single train may carry a score of staggering fever patients. The present hospitals are wholly inadequate, and in 1913 the company was erecting a new hospital at a cost of $125,000. Mr. Victor M. Cutter, manager of the Guatemala division of the United Fruit Company, states that in his district about 90 per cent of the people, including both natives and whites, suffer from malaria and its sequelæ. He thinks that approximately 20 per cent have malaria in a serious form in spite of preventive measures.

In the entire Peten strip of the Atlantic forest, from Copan on the south up through Quirigua, the lake of Izabal, and the province of Peten, it is probable that the total population does not exceed 20,000 in an area of nearly 15,000 square miles. If the cattle-raisers, mahogany-cutters, gum-gatherers, and banana-raisers be excluded, and if we include only the people who procure a living in ways possible before the coming of the white man, the population is reduced to probably less than 10 per cent of the figures given, or only 1 person for 7 square miles. Of course these figures are mere approximation; there is no such thing as a census, for much of the country is still unexplored and the wild Indian tribes practically ignore the Guatemalan supremacy. Yet day after day the traveler finds no inhabitants, and places which appear on the map as villages prove to have only two or three houses or merely an abandoned hut. Roads and even trails are almost non-existent, and in most places the machete must constantly be used to open up a pathway. Mr. Frank Blanceneaux, who for 6 or 7 years spent a large part of his time in traveling through Peten in search of mahogany, probably knows that province as thoroughly as any one. He thinks that the population does not exceed 10,000, and that at least 95 per cent of it consists of cattle-raisers, mahogany-cutters, and gum-gatherers. Nowhere has he seen a village of more than a hut or two in the genuine forest, and nowhere do people practise any real agriculture in the forest as opposed to the jungle. South of Peten, along the line of the railway from Puerto Barrios to Guatemala, for 60 miles from the Atlantic coast, until one comes to the poor little village of Los Amates, there would not be a single inhabited place were it not for the banana plantations of the United Fruit Company. Los Amates itself lies on the edge of the forest, where it breaks down into big jungle.

Whatever may be the exact figures as to population, it is evident that heavy rains, dense vegetation, and malignant fevers to-day render the Peten strip of the Atlantic forest almost uninhabitable; yet in the past this was by no means the case. Practically all of the great Maya ruins outside of Yucatan lie in this strip or in its northern and northwestern continuation in the Mexican provinces of Chiapas, Tabasco, and Campeche. Copan, one of the most remarkable of the ancient cities, lies on its edge, although not actually in it; Quirigua lies within it, although only a few miles from the border; and Seibal, Tikal, Naranjo, and a score of others as far as Palenque in the north, lie well within its dense jungle and forests. These places were obviously towns of importance, such as grow up in interior agricultural districts far from important lines of communication only when there is a considerable population round about. How dense the former population may have been we can not estimate, for the cover of vegetation is so thick that we have no idea of the exact number of ruins; but it is scarcely an exaggeration to say that for every family now supported by ordinary agriculture there was probably a town or village in the days of the Mayas.

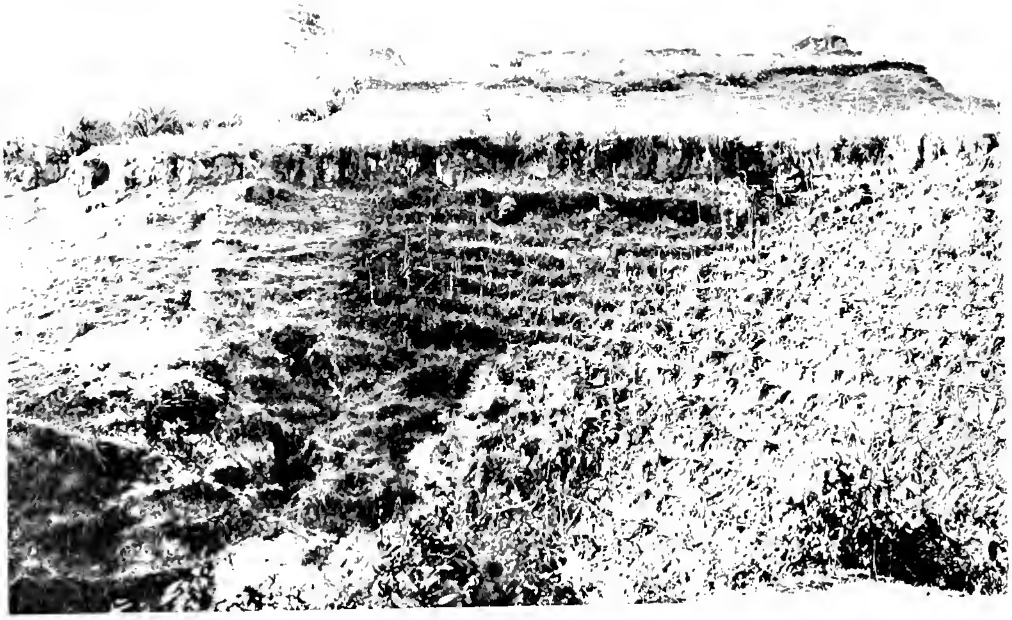
Turning now to the relatively dry portion of Guatemala, the second of our three divisions, we find it divided into arid bush country, lying in low, isolated valleys or basins, such as Zacapa, and highlands where pine or temperate forests prevail. The bush country is unimportant, being of small area. In some places it is so hot and dry that cacti and mesquite bushes make it look like the lowlands of Arizona. It is fairly well inhabited and moderately healthful. The people are in advance of the poor denizens of the forest zone, but are miserably inefficient, idle, weak-willed, and immoral. The real strength of Guatemala is in the highlands, where the vegetation takes on an aspect suggestive of the temperate zone. There, on the plateau amid pine-clad hills, all the large towns are now located. The conditions of health, from a tropical point of view, are everywhere good. Typhus, dysentery, and other disorders, to be sure, often sweep the country; and faces pitted by small-pox are frequently seen. These diseases, however, although causing a high death-rate, are temporary. Their ravages are as nothing compared with those of the deadly malarial fevers which in the lowland forests return season after season to blight and destroy the same places and the same people.

From the coast upward, according to universal testimony, the health, energy, industry, and thrift of the native Guatemalans in general show an increase. It seems a curious reversal of what we are wont to call normal conditions, when one sees rich, fertile plains along the coast almost uninhabited, then finds the population fairly dense on steeply sloping, stony mountain-sides at altitudes of 3,000 to 5,000 feet, and finally on the hilly plateau (at 8,000 feet) sees little thatched houses clustering thickly everywhere, and every available bit of land almost as carefully and industriously cultivated as in China. Even more curious, perhaps, is the fact that here, where the population is now so dense, there are relatively few important ruins and none of the advanced type found in Peten. There is no reason to think that ruins which once existed have disappeared to any greater extent than has happened in Egypt, Syria, Greece, Rome, or any other country where a high civilization in the past has been followed by a dense population at present.

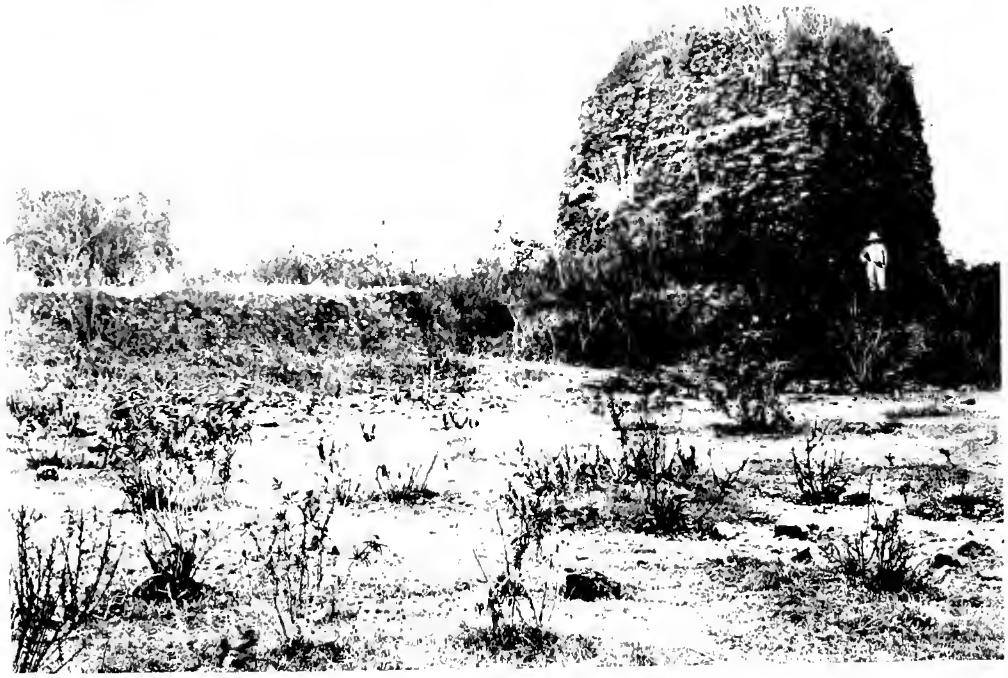
Moreover, ruins of a certain kind are found in considerable numbers, but they are insignificant and probably of late date compared with those of Peten. The carved stones which one sees, for example, at Guarda Viejo, near Guatemala City, are relatively small, crudely executed, and inartistic, utterly different from the clean-cut, highly complex, and truly artistic stelæ of enormous size at Quirigua. The plain, almost unadorned structures at Quiché, the greatest ruins on the plateau, bear to the highly developed groups of buildings and monuments at Copan about the same relation that modern Guatemalan churches bear to St. Peter's at Rome. (See Plate 10, page 211; Plate 11, page 218; and Plate 12, page 230.) In the days of the Mayas the highlands may have been as densely populated as to-day, although we have no positive proof of this, but instead of being the center of the life and activity of the country they were a provincial outpost.

Beyond the highlands, our third division (the Pacific forest) resembles the Atlantic forest in certain ways, but with interesting points of difference. As already explained, the lower slopes of the mountains and the inner edge of the piedmont plain (from an altitude of about 500 to 4,000 feet) are covered with dense vegetation. At an altitude of approximately 2,000 to 3,000 feet the vegetation attains the dignity of real tropical forest with mahogany trees, tree ferns, and the like, while on either side it assumes the form of forest-like jungle merging gradually into pine forest toward the uplands and into jungle and bush toward the coast. All except the upper mountainous part of the region is malarial and unhealthful, although not so bad as the Atlantic forest because the drainage is better. The strip of real forest would to-day be practically uninhabited were it not that the demands of the modern civilized world have led to the cultivation of coffee, chiefly by German companies with Indian labor brought from the highlands. Lower down, on the edge of the plain, there would be a small population even without the impetus of coffee. A few little towns like Retalhuleu, Santa Lucia, and Escuintla date back many centuries. They are notoriously unhealthful, however; their inhabitants are universally pronounced inefficient and apathetic; and their population of 2,000 to 12,000 people is only 10 to 20 per cent as large as that of corresponding towns on the plateau. Yet here, curiously enough, we again find abundant traces of an ancient race of relatively high culture. The ruins are

A



B



A. The ruins of Quiche, the most extensive on the Guatemalan plateau. The steep slope in the foreground shows how the volcanic tuff is dissected by precipitous canyons. It also illustrates how carefully every available area is utilized even when the only method of cultivation is the construction of very narrow terraces.

B. Near view of the most imposing ruins of Quiche. The absence of good stonework in spite of the recent age of the ruins illustrates their inferiority to those of Copan and Quirigua.

by no means equal to those of the Peten strip, and there appear to be few hieroglyphics; nevertheless, they belong to the same civilization, although to a later stage subject to foreign (Nahua) influence. At places like Baul and Pantaleon great blocks of hard basalt have been found carved with scenes of sacrifice or chiseled to represent gigantic faces whose peculiar types of slit nostril, high cheek, or projecting mouth can still be recognized in individual Indians. (See Plates 9, C, page 189, and 12, B, page 230.)

The seaward portion of the Pacific belt needs little further comment. Beginning with jungle, where the modern towns and ancient ruins come to an end, its shoreward portion is covered with dense, low bushes, among which short bamboos are often conspicuous. Although dry and parched in the winter season, much of it becomes a vast swamp when the rains swell the mountain streams and cause them to spread out over its flat expanses. Fevers then prevail and are often of the "pernicious" type, accompanied by hemorrhages of blood producing immediate death. Practically the only inhabitants are a few cattle-raisers, who are described as the lowest of the low. In the past, conditions were apparently no better, for we find no trace of ruins here.

Before we consider the possible causes of the contrast between the past and present, it will perhaps add to the clarity of our ideas if our six belts are arranged in tabular form.

TABLE 11.

Locality.	Nature of vegetation.	Health conditions.	Condition of agriculture.	Present density of population.	Condition of population.	Abundance and condition of ruins.
1. Atlantic coast	Dense forest.....	Very unhealthful	Very difficult .	Very scanty . .	Degraded	Very few so far as known, but of fairly high type.
2. Peten belt...	Dense forest with some savannas and jungle.	Very unhealthful	Very difficult	Very scanty . .	Degraded.......	Numerous and indicating the highest native American culture.
3. Dry valleys..	Bush or low jungle.	Fairly healthful.	Fairly easy . .	Moderately dense.	Low, but well ahead of 1, 2, and 6.	Moderately numerous and of fairly high type.
4. Highlands ..	Pine forest......	Healthful	Easy........	Very dense...	By far the best in Guatemala.	Quite numerous, but mostly of rather low type, that is, provincial or degenerate.
5. Pacific coffee belt.	Forest and jungle..	Unhealthful....	Fairly difficult	Rather scanty.	Low, but ahead of 1, 2, and 6.	Moderately numerous and of fairly high type.
6. Pacific coast	Bush......	Very unhealthful	Difficult .	Very scanty.	Degraded	None so far as known.

It is worth while to emphasize the strange contrast between past and present. The belts along the Atlantic and Pacific coasts may be left out of account, since in the past, as at present, they appear to have been too forested and too feverish for human occupation to any great extent. To-day the other four divisions stand in the following order so far as progress, achievement, and density of population are concerned: first, the highlands; second, the dry valleys; third, the coffee belt; fourth, the Peten strip. In the past the ruins tell a very different tale: the Peten strip stood first, then the coffee belt and the dry valleys, and last of all the highlands, the reverse of the present order. To-day, in Central America, the physical conditions under which mankind tends most to increase in numbers and to progress in culture appear to be high altitude, good drainage, and a fairly long dry season. Altitude in itself, however, does not appear to be essential, for northern Yucatan seems as well off as the highlands of Guatemala. Perhaps the exposure of that part of Yucatan to the ocean and to strong winds from the north produces the same effect as elevation. Opposed to these favorable conditions stand those which conspire to hold man back and keep him in a low stage of civilization. Omitting low altitude, which is important merely because of its effect on other factors, we are confronted by four chief conditions: first, the prevalence of fevers; second, the prevalence of great heat and moisture almost without change from season to season; third, the difficulty of carrying on permanent, intensive agriculture; and fourth, the relative ease of getting a living in the jungle.

Little by little the world is learning that the most dangerous diseases are not necessarily those which show the highest death-rate. The plagues of the Middle Ages loom large in history, but they did not do a tithe as much harm as syphilis has done. Yellow and typhus fevers may decimate a population, but they are far preferable to the slow, irresistible ravages of recurrent malarial fevers, which rarely seem to kill, but merely undermine the constitution, leaving both mind and body inefficient. Tuberculosis, in our own land, is so dreaded that we wage a crusade against it, but its dangers are probably far less than those of the insidious colds which year after year attack fully half of our northern populations, not killing them, not even doing more than lessen their efficiency for a few days, and yet in the aggregate causing an incalculable amount of damage and giving an opening for a large part of our cases of consumption, diphtheria, deafness, and many other afflictions. Just as in our huge folly we long neglected consumption, and still largely neglect the even more insidious ordinary colds, so the man within the tropics often ignores malaria. Again and again I have talked with people who said there was no fever in the particular place where they lived or that they had not had fever, but before the next meal they took a dose of quinine, and that same night, perhaps, they reeled with a touch of fever or shivered with a chill. They called it "nothing," but even quinine did not prevent them from being weakened by it. Few foreigners, especially children, can live long in the lowlands under ordinary conditions without being affected. As for the natives, it is often stated that they become immune to fevers, but here is what Sir Ronald Ross, of the Liverpool School of Tropical Medicine, and one of the chief authorities on the subject, has to say:

"These diseases do not affect only immigrant Europeans; they are almost equally disastrous to the natives, and tend to keep down their numbers to such a low figure that the survivors can subsist only in a barbaric state. To believe this one has to see a village in Africa or India full of malaria, kala-azar, or sleeping sickness, or a town under the pestilence of cholera or plague. Nothing has been more carefully studied of recent years than the existence of malaria amongst indigenous populations. It often affects every one of the children, probably kills a large proportion of the new-born infants, and renders the survivors ill for years. Here in Europe nearly all our children suffer from certain diseases—measles, scarlatina, and so on. But these maladies are short and slight compared with the enduring infection of malaria. When I was studying malaria in Greece in 1906 I was struck with the impossibility of conceiving that the people who are now intensely inflicted with malaria could be like the ancient Greeks who did so much for the world; and I therefore suggested the hypothesis that malaria could only have entered Greece at about the time of the great Persian wars—a hypothesis which has been very carefully studied by Mr. W. H. S. Jones. One can scarcely imagine that the physically fine race and the magnificent athletes figured in Greek sculpture could ever have spent a malarious and spleno-megalous childhood. And conversely, it is difficult to imagine that many of the malarious natives in the tropics will ever rise to any great height of civilization while that disease endures amongst them. I am aware that Africa has produced some magnificent races, such as those of the Zulus and the Masai, but I have heard that the countries inhabited by them are not nearly so disease-ridden as many of the larger tracts. At all events, whatever may be the effect of a malarious childhood upon the physique of adult life, its effects on the mental development must certainly be very bad, while the disease always paralyzes the material prosperity of the country where it exists in an intense form.

"Consider now the effects of yellow fever, that great disease of tropical America. The Liverpool School sent four investigators to study it, and all these four were attacked within a short time. One died, one was extremely ill, and two suffered severely. The same thing tended to happen to all visitors in those countries. They were almost certain of being attacked by yellow fever, and the chances of death were one to four. But malaria and yellow fever are only some of the more important tropical diseases. Perhaps the greatest enemy of all is dysentery, which in the old days massacred thousands of white men, and millions of natives in India, America, and all hot countries, and rendered survivors ill for years. Malaria has always been the bane of Africa and India; the Bilharzia parasite of Egypt; and we are acquainted with the ravages of kala-azar and sleeping sickness. Apart from these more general or fatal maladies, life tends to be rendered unhealthy by other parasites and by innumerable small maladies, such as dengue and sand-fly fever, filariasis, tropical skin diseases, and other maladies, * * * True, we have many maladies in Europe, but in order to compare the two sets of diseases we should compare the death-rates. Whereas in England it is a long way below 20 per 1,000 per annum, throughout the tropics it is nearer 40 per 1,000. In India alone malaria kills over 1,000,000 persons a year, and dysentery and malaria kill many hundreds of thousands. I have seen places in which the ordinary death-rate remains at between 50 and 60 per 1,000; others which were so unhealthy that they were being deserted by their inhabitants; and others, lastly, which were simply uninhabitable. What would people say if such a state of things were to exist in most villages in England, Scotland, and Ireland?"*

On the whole, it seems safe to say that in tropical countries the density of population and the stage of culture depend to a large extent upon the amount and kind of fevers; yet fevers are far from being the whole story. Few who have ever been in the torrid zone will deny that under prolonged and unvarying conditions of heat and dampness both physical and mental energy decline. One is tempted to sit down idly and rest and enjoy the warm air. When it is time for a new piece of work one tends to hesitate and to be uncertain as to just how to begin. Of course there are exceptions, and of course a long inheritance of activity in cooler regions will for years largely overcome these tendencies. Nevertheless, of the scores of northerners, both American and Europeans, whom I have questioned in the torrid zone there was scarcely one who did not say that he worked less than at home. At first a considerable number said that they had as much energy as at home, but then they added that it was not necessary to work so hard, and moreover that they did not feel like it. Much more striking was the absolute unanimity with which they said that when they experienced a change of climate, especially if they went from lowlands to highlands, or still more when they returned to the north, they at once felt an access of energy which lasted some time after their return. To a New Englander accustomed to look upon our Southern States as having a warm, debilitating climate, it is interesting to hear people in Guatemala speak of being stimulated as soon as they feel the cool winter air of New Orleans. The natives of the torrid zone are of course so accustomed to the heat that they enjoy it and suffer from even a slight degree of cold, but the very fact of being accustomed to the heat seems to carry with it the necessity of working and thinking slowly. The universality with which this is recognized in Central America is significant. Again and again, when one asks about labor conditions in specific places, one is told, "Oh, yes, the people there are all right, but you know it's always hot down there and they don't work much." All this, I know, is perfectly familiar, but it deserves emphasis because the great ruins are practically all in the hot country where "they don't work much."

In addition to debilitating fevers and an enervating uniformity of warm, moist atmospheric conditions, tropical countries suffer from peculiar agricultural conditions. As we have already seen, in the great forest, where rain falls at all seasons, the making of clearings is practically impossible. In the dense jungle, such as that at an elevation of 1,000 to 2,000 feet in the Pacific coffee belt of Guatemala, this is usually but not always possible. It depends on the length and character of the dry season in February, March, and April. Between two and three weeks of steady sunshine are said to suffice to prepare the cut bushes and smaller branches of the trees for burning, but sometimes there is scarcely a rainless week during the whole year. This happened in 1913. People who chanced to do their cutting early burned their fields and were able to plant a corn crop, but many cut too late and failed. It is easy to say that everyone ought to cut and burn early, but in the first place the lethargy of the torrid zone leads people to put things off till the last moment. In the second place, if the land is burned over too early, weeds and bushes will sprout and grow to a height of a foot or two before it is time to plant the corn. Hence a second clearing will be necessary, and if a second burning is impossible the corn will be at a disadvantage.

* United Empire, February 1913, pp. 123–124. Sir Ronald Ross: Medical Science and the Tropics.

This does not end the difficulties of agriculture in the dense jungle. The first corn crop from a given clearing is usually very abundant, but the second, if it follow immediately after the first, is poor, so poor that it is scarcely worth raising. Perhaps this is because the abundant vegetation and constant rains cause many important chemical ingredients to be leached quickly from the soil, or perhaps for some other cause. At any rate the regular custom is to cultivate a given tract one year, let the bushes grow four years, till they are perhaps 15 to 20 feet high, and in the fifth year cut, burn, and plant again. Thus agriculture in the dense jungle is not only precarious, but it is forced to be extensive and superficial rather than intensive and careful; therefore it does little to stimulate progress. In the drier regions, whether high or low, the soil is not so quickly exhausted, especially if the absence of roots or other conditions make it possible to turn up new soil by plowing or otherwise. The crops are by no means so abundant as in the wetter places, but the same land can be cultivated year after year with only short periods of rest. The cultivator must work harder than in the wet places, but his success is less precarious, the efforts of one year have a direct bearing on succeeding years, and permanent industry is encouraged.

Still another disadvantage of the low, wet regions needs to be briefly discussed. It is hard for mankind to get a living under any circumstances in the genuine tropical forest, and he must work at least moderately for one in the dry parts of tropical lands. In the big jungle, however, game is abundant, wild fruits ripen at almost all seasons, a few banana plants and palm trees will almost support a family, and if a corn crop is obtained at all, the return is large in proportion to the labor. Thus, so long as the population is not too dense, life is easy and there is little stimulus to effort. Under such conditions the state of human culture is not likely to improve, for only by a revolutionary access of skill and industry would it be possible to change from the easy, hand-to-mouth life of the present to the intensive, industrious life which seems to be a necessary condition where civilization makes genuine progress.

Thus far in this chapter we have seen that the distribution of population in Guatemala to-day is very different from what it was in the past. We have further seen that the physical conditions which make for density of population and increase of civilization are distributed in a peculiar fashion. They prevail in the highlands, where there is no evidence that the civilization of the past was any higher than that of the present; and do not prevail in the lowlands, where there is clear evidence of the existence for many centuries of a civilization far in advance of that of to-day. Moreover, the ancient civilization did not come to the country full-fledged, as did that of Spain in later times. It did not do its finest work at once and then decline, as did that of the Spaniards after they had built their massive old churches. On the contrary, it apparently arose where we find its ruins, and it endured for centuries before it decayed. The most fundamental fact is not the great change which has taken place in the character of the Maya race. Nor is it the fall of Maya civilization, whether from internal decay or external attack. It is merely the simple fact that the highest native American civilization grew up in one of the worst physical environments of the whole western hemisphere. Close at hand, in the Guatemalan highlands on one side, and in the dry strip of northern Yucatan on the other, far more favorable environments were occupied by closely allied branches of the same race, but the greatest civilization grew up in the densely forested, highly feverish, and almost untillable lowlands of Peten and eastern Guatemala.

The explanation of this peculiar state of affairs appears to lie in one or all of three things: first, the character of the Maya race; second, the relative abundance and virulence of various diseases; and third, the nature of the climate and its effect on forests, diseases, and agriculture. It is possible to adopt the usual unexpressed assumption of historians and to suppose that the original Mayas were stronger and more virile than any other race which has entered the torrid zone, and that because of some unexplained stimulus, whose nature it is hard to surmise, they flourished greatly in a habitat in which modern races can barely subsist. The theory that the Mayas were different from other races has a good deal to commend it. They certainly were a remarkable people. The only question is how remarkable. The nearest analogue to their achievements is found in the ruins of Indo-China, Ceylon, and Java. In none of these cases, however, was the degree of success (as measured by our formula of achievements divided by opportunities) anything like so great as among the Mayas. The Asiatic races appear to have been like the Spaniards, invaders who did not develop a new civilization, but brought their ideas with them from other places where we can still see remains of the parent culture; moreover, they did not rise to the height of inventing a method of writing, and, in Indo-China at least, they had the advantage of tools of iron. Nevertheless, when their history is finally understood, we shall perhaps ascertain that their civilization and that of the Mayas arose under similar conditions because of similar causes. This, however, is aside from the question. The important point is that no matter how capable we suppose the ancient Ceylonese, Indo-Chinese, and Javanese to have been, the Mayas were still more capable, for not only were their achievements greater than those of the others, but their opportunities were less. Hence, if we explain the rise of Maya culture solely on the basis of racial character we are forced to assume that the ancient Mayas were not only almost immeasurably in advance of any race that now lives under a similar environment, but were more competent than any other race that has ever lived permanently in any part of the torrid zone. Indeed, in their achievements in overcoming an adverse environment, we are perhaps obliged to put them on a pinnacle above any other race that has ever lived.

Without denying that the Mayas were a remarkable people, let us entertain the further hypothesis that in the days of their greatness tropical fevers either had not been introduced into America, or were by no means so virulent as now. This helps us greatly, for it relieves us of the necessity of assuming the Mayas to have possessed a degree of resistance to fevers far in excess of anything known to-day. There are, however, grave objections to this hypothesis. In the first place, it is a pure assumption entirely unsupported by any independent evidence. In the second place, tropical diseases are numerous, and even malarial fevers are of several kinds. We may readily suppose that one or two diseases may have been introduced into Central America between the time of the Maya civilization and the Spanish Conquest, but in the entire absence of any evidence it is a rather large assumption to suppose that many diseases were thus introduced and that they were able to work so great a revolution. Thirdly, this hypothesis does not explain why the advancement of civilization went on so rapidly and for so long in spite of the enervating effects of almost unchanging heat and dampness. Nor does it explain why the Maya civilization reached the coast at only one or two spots. So far as topography is concerned there is nothing to prevent this on either coast. Much of the narrow Pacific plain could be cultivated with ease, even though swamps do cover part of it, and on the Atlantic side the parts of the forest where there are no ruins seem to be no worse than those where they exist. The native inhabitants of this region all appear to have been of Maya stock, even though they may not have belonged to the main branch. Under such circumstances it hardly seems as if so progressive a civilization could have existed many centuries without extending its influence to the coast in British Honduras, unless there had been some preventive such as fever.

The assumption that in Central America tropical diseases were formerly less abundant or less baneful than now relieves us of the necessity of supposing that the Mayas, remarkable as they were, possessed a degree of immunity or resistance to disease far in excess of that of other races, but it does not relieve us of other difficulties. Moroever, as it now stands it has the weakness of being a pure assumption with no assignable cause and no independent evidence. If, however, we supplement our assumptions as to the character of the Mayas and as to the prevalence of disease by the further assumption of climatic changes such as have been inferred in previous chapters, practically all the difficulties vanish. The Mayas, on this supposition, lived in an environment as favorable as any now found within the tropics. They did not suffer greatly from tropical diseases because the physical conditions were not favorable to the propagation of harmful species of mosquitoes.

The sort of climatic change which we have inferred would involve the following conditions at the height of the Maya civilization: In the first place, the dry season would have been longer, more windy, and colder than at present. This would not have influenced the coastal strip so much as the interior. Hence the coast may have had considerable forests or at least dense jungle, and may have been feverish. Farther in the interior, however, where the ruins are chiefly located, relatively dry conditions would have prevailed like those of northern Yucatan to-day, save that the contrast of seasonal temperature would have been greater. Thus the habitat of the malarial species of mosquitoes would have been much reduced, and fevers would have been to a considerable extent relegated to the coastal forests, which therefore would have had little population. In addition to this the enervating influence of climatic uniformity would have been somewhat relieved, and agriculture of the intensive kind would have been possible in the Peten plain, just as it is to-day in northern Yucatan. The areas of big jungle where life is excessively easy so long as the population remains uncivilized and comparatively scanty, but where intensive agriculture is to-day difficult, would have been much reduced. Thus the Peten region, being a fertile lowland, would have been a natural center of civilization. In other words, the adoption of the climatic hypothesis does not lead us to abandon our hypotheses as to racial character and disease. It merely removed from them certain elements of improbability. It supplies the elements which the other hypotheses lack, and in addition it possesses the strength of being supported by strong external evidence.

In this last statement lies the chief significance of the present chapter. Our climatic hypothesis was framed, crudely at first, in Russian Turkestan and Persia; it was revised in Chinese Turkestan and India; modified greatly by studies in Palestine and Asia Minor, and confirmed apparently by the burial of Olympia, by the distribution of population in Greece, and, so it seems, by what others describe in North Africa. It was further confirmed, but again much modified, by ruins in the southwestern United States and by the trees of California. Finally, it was applied to the torrid zone in Yucatan and seemed to fit the facts. Now it has been carried to another tropical region where a fuller test is possible. Here again, down to such minute details as small fluvial terraces, it seems to be in accordance with the facts. Doubtless it will be further modified; doubtless I have ascribed to it some results really due to other causes, but that is an inevitable stage of a new subject. The only question is, how far does the present theory harmonize with the great body of facts by which it has been, or may in future, be tested? So far as it does, we may tentatively accept it. So far as it does not, it must be revised.

CHAPTER XVIII.

CLIMATIC CHANGES AND MAYA HISTORY.

As a last step in our investigation of climatic changes in Central America let us briefly consider Maya history and see how the future elucidation of this most perplexing subject will either disprove certain parts of our hypothesis, or else greatly strengthen them. Let us first state what expectations the hypothesis would lead to and then compare them with the conclusions of the best authorities on Maya history. For the thousand years previous to the time of Christ, to judge from figure 50, on page 172, the general climatic conditions were such that in subtropical regions, like central California or Palestine, the driest times were as moist as the wettest times are at present. This seems to mean a pronounced displacement of the zone of westerly storms toward the south, especially in winter. Therefore in winter the whole Maya country probably had a long dry season comparable to that which now prevails only in the relatively progressive region of northern Yucatan. Under such circumstances jungle rather than forest would be the prevalent growth over the whole area, and the contrast between summer and winter would be greater than it is now in any part of the country. Thus the two chief drawbacks to civilization, namely, the feverish, irreclaimable forests and the deadening climatic monotony, would be in part removed. A thousand years of such conditions would give opportunity for the growth of civilization, which we should expect to find making rapid strides from the sixth to the fourth century B. C., falling off then somewhat for 200 years, rising again during the second century, and continuing at a high level for 200 to 300 years. Then from 200 A. D. to 650 A. D., as appears in figure 72 on page 209, which is merely a part of figure 50 with an enlarged vertical scale, the general tendency would be downward, with an interruption perhaps in the sixth century, but reaching a very low ebb in the seventh. The long decline of the California curve of figure 50 from soon after the time of Christ to 650 A. D., it must be remembered, is probably more important than the apparently sharper and greater declines of earlier times, for those are exaggerated because of the small number of trees available more than 2,000 years ago. During the decline after the time of Christ the southern parts of Maya land would suffer first and might so far revert to true forest as to become uninhabitable by any one except wandering savages, while the northern parts would still possess comparatively favorable conditions. In the seventh, eighth, and ninth centuries we should expect that conditions would be no better than at present. Forests would naturally prevail wherever they are now found, the area where civilization is possible would be restricted to northern Yucatan, and the people would be steadily weakened by fevers and a warm, monotonous climate. Before their energy was wholly sapped, however, and before the ancient culture had completely disappeared, improved conditions, beginning about 880 A. D. and lasting two centuries, would cause a revival; the forest belt would be pushed back somewhat, but not so far by any means as at the time of Christ, and for a time the greater contrast of the seasons would help to stimulate the people. Then would follow a decline culminating about 1300 A. D. At the beginning of the fourteenth century another revival of culture might be expected, but it would be of slight importance for two reasons: In the first place, the adverse conditions of the twelfth and thirteenth centuries would probably have reduced the jungle-covered area to small extent and would have brought the vigor of the people to a condition even lower than was reached in the preceding adverse period. In the second place, the favorable period is limited to about a hundred years, chiefly during the fourteenth century, too short a time to produce very pronounced effects. Then would come a third relapse, which would probably bring the people to a lower state than ever by 1500 A. D., just before the Spaniards arrived. Since that time a slight but unimportant recovery might be looked for, but its magnitude would depend on whether our sequoia curve should lie in the upper or lower of the two positions indicated in figure 72.

Before comparing this inferred history with that which actually occurred, two signals of warning must be set up. In the first place, I would not be understood to imply that climatic changes, with their attendant physiological, pathological, economic, and political results, are the only or main cause of historic events. Doubtless races, like individuals, go through a definite development from youth to maturity and old age. Doubtless such circumstances as luxury, contact with other races, the introduction of new ideas, and the commanding genius of gifted individuals are so important that any one of them may completely reverse the effects of physical environment. Nevertheless, the environment continues to act. An injurious change, like a slow, wasting sickness, may perhaps cause a youthful nation to age prematurely, while a beneficial change, like the cure of a chronic disease, may restore a youthful buoyancy which had seemed to be forever lost. These things will not change the laws of the rise and decay of nations, nor will they nullify the effect of ideas, inventions, genius, and the thousand other factors which enter into history. The case is exactly like that of a human being. Nothing can prevent him from passing from youth to maturity and old age; sickness need not necessarily prevent him from enjoying the advantages and stimulus of friendship, reading, and travel; a new interest may temporarily or even permanently overcome a physical weakness that has hitherto prostrated him, and he may die in his youth and strength through accident, or may linger on to extreme old age in spite of chronic illness. Yet all these things do not mean that disease has no effect or that it is not highly important. And so it is with physical environment; favorable conditions will not make a stupid race brilliant, nor will unfavorable conditions destroy the natural abilities of a race that is gifted. Nevertheless, changes of climate, like the coming and going of disease, may help or hinder the progress or decline which is taking place as the result of the complex interplay of all the many factors that control historic development.

Our second warning signal is necessitated by the extreme scantiness of our knowledge of early Maya history. The chief sources of knowledge are, first, certain chronicles which were pieced together after the arrival of the Spaniards and were written in the Maya language but with Spanish letters. They pertain only to northern Yucatan and are often confused and inaccurate, but have a distinct historical value. A second but as yet unusable source of knowledge is three or four codices of pre-Spanish date written in Maya hieroglyphics, but the key to their interpretation has not been found and the only intelligible portion is certain calculations. Many such codices existed at the time of the Spanish conquest, but the conquerors, in their zeal for religion, burned all they could lay their hands upon. A third source of knowledge is a considerable number of stelæ, lintels, and other monuments, found in connection with temples and bearing dates according to the old Maya calendar. These, unfortunately, are confined to the southwestern portion of Maya land, and only one or two have been found in northern Yucatan. The most important is upon a lintel at Chichen Itza, the greatest city of the region. Finally, our best knowledge of the Mayas is derived from the nature and development of their art and architecture, a subject which has been carefully investigated by Mr. H. J. Spinden, in his recent work, "A Study of Maya Art."* He there sums up the evidence derived from the various sources of knowledge and displays it graphically in a chronological table. Unfortunately, however, the study of art and architecture does not furnish exact dates. Therefore we still remain in great uncertainty as to all but the main outlines of Maya history, and the statements which follow must be regarded as largely tentative.

* Memoirs of the Peabody Museum of American Archæology and Ethnology, Harvard University, 1913.

The paramount difficulty in Maya history is the correlation of the ancient and recent Maya calendars with one another and with the European system of chronology. The complexity of the matter may be illustrated by the fact that the date of Stela 9 at Copan is interpreted by Seler as 1255 B. C., by Bowditch as 34 A. D., and by Morley as 288 A. D. The trend of recent opinion seems to be that Seler's date is much too early, but the entire matter is still an open question. The ancient Mayas who built the ruins and the modern ones who wrote the chronicles just after the Spanish invasion used the same highly complex calendar, but with slightly different adjustments and varying degrees of completeness. The major units of this calendar were the "tun," having a length of 360 days; the "katun," consisting of 20 tuns; and the cycle, composed of 20 "katuns," or approximately 398 years. According to the ancient method every date consisted of 5 numbers, indicating the cycle, katun, tun, month, and day. In later times this cumbersome method was abandoned and seems to have passed out of use several centuries before the coming of Europeans. An abbreviated system was in use at the time of the Spanish conquest and the great problem of Maya chronology is to correlate this with the ancient system and with the European chronology. One of the peculiarities of both ancient and later calendars was that each katun or 20-year period began with a day called "Ahau." The Ahau was a sequence of 13 days, and different days were designated as 1 Ahau, 2 Ahau, etc. It so happened that the Ahau days with which successive katuns began fell in the following sequence: 13, 11, 9, 7, 5, 3, 1, 12, 10, 8, 6, 4, 2. Among the later Mayas the dates were simply indicated by giving the number of the day Ahau with which the given katun began. Hence, while the old method fixed the date for all time, provided the year 1 were definitely known, the later method only fixed its relative position in the period of 260 years making up the 13 katuns of a single series of katuns beginning with the 13 Ahau days. It is as if we were to abandon the use of the numbers indicating centuries in our era and to write only the last two figures of our dates. If we did this we should know that the years '20 and '50 were 30 years apart, provided that they fell in the same century, but if we had two such dates and did not know their centuries one might be 1220 and the other 1550. Thus in using the later Maya calendar great care must be exercised in order not to confuse the various 260-year periods, for otherwise the chronology becomes utterly unreliable and the time of any event may be displaced by 260 years or by some multiple of 260.

Maya chronology, as Spinden expresses it, "rests upon a tripod foundation, one leg being the chronicles preserved after the coming of the Spaniards, another leg being the inscribed dates, and the third being the natural order of art and architecture. The earliest period is strong through the practical coincidence of the inscribed dates and the natural order of the art. The latest part of the history is equally certain on account of the fullness of the traditions. The intermediate period is the only one which as yet has been incapable of strong reinforcement." The traditional history of the Mayas was recorded in the Maya language, but in Spanish letters not long after the Conquest. It is fairly full for later times, but of course becomes less and less dependable as we go farther into the past. Its dates are given in the abbreviated later style, but as this was still used at the coming of the Spaniards the dates can of course easily be determined in the European calendar. Farther back the danger of mistakes greatly increases, but for five or six centuries it does not become serious, for the errors must amount to 260 years, and so are easily avoided. Back of about 900 A. D., however, the traditions become scanty and confused and the possibility of errors increases enormously. The traditional history is connected with that of the dated monuments only most vaguely. For example, it refers to the "discovery" of Chichen Itza and to its abandonment and reoccupation, but at Chichen Itza only a single date has been found, upon a lintel. This lintel does not seem to be in its original position, but to have been rebuilt into a new structure after the old one had fallen to ruins.

Turning now to the ancient monuments, the dates on these are all given in the full form, including the cycle, katun, and tun. Hence they can be placed with precision in their relation to one another. The only difficulty lies in reading them, for being inscribed chiefly upon soft limestone they are in many cases so worn that it is difficult to decipher them, and various authorities often disagree in this matter. Nevertheless, it is fairly easy to elucidate the chronology of several centuries during which monuments are abundant. If a single date recorded according to the ancient system could be unmistakably correlated with our European calendar the problem of dating the monuments would be solved. In one case the date of the death of a chief named Ahpula, who died in 1536 A. D., has been recorded in this way in a manuscript written after the coming of the Spaniards. Bowditch,* one of the best authorities on the Maya calendar, considers that this is the most reliable link between the European calendar and the monuments. There are various difficulties, however, and the matter is by no means so simple as it appears. For example, in late Maya times the position of each day in its month had somehow been slightly shifted from its position in the inscriptions, and we are uncertain just what effect this may have had on the count. The other chief method of determining the relation of the dates on the monuments to the European calendar is that followed by Morley. On the basis of tradition he determines the probable date of the two occupations of Chichen Itza. The date on the lintel there is read as the second katun of the tenth cycle, or katun 3 Ahau, according to the later system. The problem then becomes to find a period of occupation that includes the katun 3 Ahau. Morley solves this by putting the date in the first period of occupation, which also seems to be the only possible position for architectural reasons. The resulting coincidences are regarded by Spinden as so remarkable that he considers that they solve the question of Maya chronology, but this opinion is by no means universally shared by archæologists. To the layman it seems as if Bowditch had employed the most reliable method of determining the relation of the dates on the monuments to the European calendar, while traditional dates seem to be the only way of arriving at the chronology of the period after the last monuments. The artistic sequence, on the other hand, is highly valuable at all times as a check upon the others and as a means of bridging the gap where no other information is available.

Leaving now this intricate problem of Maya chronology, let us briefly review the history of the country. Perhaps the most convenient summary is given in Spinden's guide to the Mexican Hall of the American Museum of Natural History in New York. The accuracy of his dates, as we have already indicated, can not yet be determined, but as to the general sequence of events there is substantial agreement. The earliest date yet found upon any piece of Maya work is recorded on the so-called Tuxtla statuette. Its decipherment is doubtful. Morley makes it about 113 B. C., Bowditch about 365 B. C., and Seler nearly 1,300 years earlier than Bowditch. The next date is found upon the so-called Leiden plate. It probably falls about 160 years after that of the Tuxtla statuette, and can be read with much greater certainty. These two dates indicate that at least a century, and perhaps sixteen or seventeen centuries, before the beginning of the Christian era the Mayas had reached so high a state of civilization and had so long preserved exact records of the movements of the sun and stars that they had framed a calendar more exact than any used in Europe or Asia until the adoption of the Gregorian calendar in 1582 A. D. To accomplish this they must for many years have been able to record their observations in permanent form. Hence we must conclude that for centuries prior to 375 B. C., to use Bowditch's dates, the Mayas had been a highly progressive and intelligent people.

About a hundred years after the date of the Leiden plate the Maya civilization had reached so high a development that important cities began to arise in the south, especially

* C. P. Bowditch, Memoranda on the Maya calendars used in the books on Chilan Balam, American Anthropologist, n. s., vol. 3, 1901, pages 129 to 138.

such places as Tikal, Copan, and Quirigua. Great temples were erected upon enormous mounds, and public squares were adorned with stelæ and altars. The earliest dated monument, according to Morley and Spinden, is Stela 3 at Tikal, to which Morley assigns the date 214 A. D. The next is at Copan, where Stela 15 was erected 37 years later than the Tikal stela. According to Bowditch, however, Quirigua is decidedly older than Copan. He considers that Stela C at Quirigua dates from 75 B. C. and that Stela K, the last stela at that place, bears the date 275 A. D. The monuments at Copan, on the other hand, are held by him to range from Stela 9, 34 A. D., to Stela N, 231 A. D. When Hewett* began to excavate at Quirigua, however, the first temple which he uncovered proved to have been built five years after the erection of the last monument, and other temples may have been erected still later.

In all of these earlier sites the older monuments are crude and archaic, but the style grows gradually better and apparently culminates at about the time of the erection of the last monuments. During the later part of the period when these great cities flourished in the south of Maya land, many others sprang up in the region farther north, for example, Seibal, Yaxchilan, Piedras Negras, and Palenque. These apparently never reached quite so high a stage of culture as the earlier cities. Their architecture may be more striking, but the carving on the monuments is not so truly refined and skilful. They seem to indicate that toward the close of the period of greatest Maya development there was a gradual northward movement of civilization, accompanied by the beginnings of decline.

Soon after 600 A. D. according to Morley and Spinden, or after 350 A. D. according to Bowditch, the decline of Maya civilization culminated in a serious collapse. The southern cities were apparently completely deserted, for as yet we have no evidence of any long occupation after the time of the latest dated inscriptions. Only in northern Yucatan does any semblance of civilization appear to have remained. There Chichen Itza appears to have been founded at about this time, or at least a certain amount of building was going on there, since we have a lintel which bears a date which Morley interprets as 603 A D., and which according to Bowditch's system would fall about 350 A. D. Yet even in the north, Maya civilization seems to have been at an extremely low ebb, and there was apparently little improvement until almost the beginning of the tenth century. Doubtless many buildings were erected in northern Yucatan during the intervening centuries, but they must have been comparatively unimportant, since scarcely a trace of them has been found. This period may well be called the Dark Ages of Maya history, although a later period, just before the Spanish Conquest, was perhaps equally dark. The Dark Ages were followed by a marked revival. The date of this can not be determined from monuments, but only from the traditional accounts, for the Mayas of the Renaissance, as we may call this period, did not date their monuments and temples with the care used by their ancestors. Nevertheless, it seems fairly certain that the tenth and eleventh centuries were the time of the erection of the truly remarkable series of great buildings whose ruins even now excite our wonder in northern Yucatan. Chichen Itza was apparently re-established at this time after a period of desertion. Uxmal and Mayapan were also built, and these three cities formed a league. Many other towns, such as Kabah, Labna, Sayal, and Izamal, seem also to have flourished, but we have no traditions of any except Izamal. The architectural remains of this period are to-day the most imposing ruins in any part of the Western Hemisphere. Nevertheless, although they appear more impressive than those of earlier times, they do not represent so high a type of architecture. Stelæ and other carved monuments, for example, are almost unknown, and easily prepared wooden lintels are substituted for the more laboriously prepared stone type. New ideas are not so abundant as formerly, and the general aspect is that of the revival of an earlier art without its originality.

*Edgar L. Hewett, Two Seasons' Work in Guatemala, Proceedings of the Archæological Institute of America, June 1911, pp. 117–134. The Third Season's Work in Guatemala, ditto, June 1912, pp. 163–171.

Another noticeable feature is that the culture of this time did not persist long. By 1,200 A. D. or earlier, serious civil wars appear to have broken out, and in general a period of relative instability ensued. Spinden describes this period as follows:

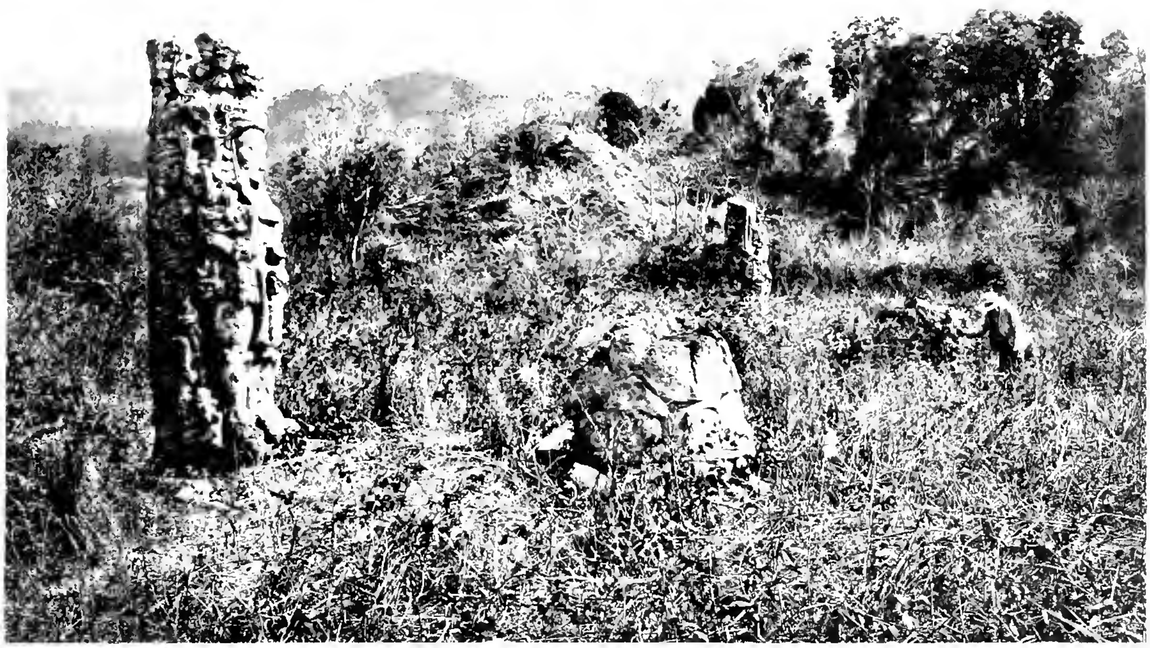
"After the fall of Mayapan the Mayas seem to have been divided into many warring factions. All the great cities were abandoned, although the temples were still regarded as sacred. Of course, stonebuilt architecture was still prevalent, as we know from some of the early descriptions of towns on the coast. Learning was still maintained by the nobles and the priests. But there was not the centralized authority necessary for the keeping up of such luxuriant capitols as existed in the old days. At the present time certain ancient ideas still persist, as has already been stated in connection with the ethnology of the Lacandone Indians. Upon the western highlands there is another body of traditions which concern the Quiche, Cakohiquel, and other Mayan tribes, but do not go back for more than 200 years before the Spanish Conquest and are of very little real service. All in all there is little to be said in favor of the frequent plaint that the coming of the white man snuffed out a culture that promised great things. The golden days of the Maya civilization had already passed, and, if we may judge by the history of other nations, would never have returned."

To sum up the whole matter, the outstanding facts in Maya history seem to be as follows: First, we have a long period of active development, during which the calendar was evolved, and the arts of architecture and sculpture were gradually developed, although few tangible evidences of this now remain. This time of marked growth, according to all authorities, must have preceded the Christian era. Then comes a period when the previous development flowered, as it were, in the building of the great cities of Copan, Quirigua, Tikal, and presumably many others less well known. These first great cities were in the southern part of the Maya area, on the borders of Honduras, or in eastern Guatemala. They lasted perhaps three or four centuries, and then quickly declined. So far as we have any evidence, civilization never revived in this southern area, for the structures of the great period have not been rebuilt by later inhabitants. Toward the end of the period of greatness the center of Mayan culture moved northward into northern Peten and the Mexican provinces of Tabasco, Chiapas, and Yucatan. The great period, according to Bowditch, lasted from approximately 100 B. C to 350 A. D. The more northern cities, perhaps, flourished a little after this time, but not for long. Then there came a time of very low civilization, lasting for centuries. Apparently during these dark ages northern Yucatan was the only place where civilization survived. A revival ensued about 900 or 1,000 years after Christ, and architecture once more reached a high pitch. Yet there was no such originality as during the earlier period, and marked progress was made only in northern Yucatan; all the rest of the country seems to have remained in darkness. Moreover, this mediæval revival was relatively short-lived. We do not know its exact duration, but apparently most of the important buildings were erected within the space of one or two centuries. Since that time the condition of the Mayas has fluctuated more or less, but on the whole there has been a decline.

Already the reader has doubtless seen that the general history of the Mayas, in its broader features, agrees with what we should expect from the pulsatory theory of climatic changes; that is, there have been alternate periods of growth and decline, which occur in just the way that we should expect on the supposition that changes of climate have been an important factor in determining whether civilization was possible or not. If Bowditch's method of dating Maya chronology is correct, times of favorable climatic conditions, as indicated by our California trees, have also been times when the Mayas reached a high stage of civilization. If the system of Seler is correct, there is probably also the same kind of agreement, although this has not yet been carefully tested. If Morley and Spinden are correct, on the other hand, the events of Maya history since 600 A. D agree quite closely with our expectations, but previous to 600 A. D. the agreement holds only imperfectly. For the sake of convenience, the whole matter is summed up briefly in Table 12. The

A

B



A. Stelae inscribed with hieroglyphics at Quirigua, dense tropical forest in background

B The ruins of Copan. When discovered the ruins were covered with large trees like those on the right. The mounds in the middle foreground are the main ruins.

dates are, of course, only approximate. They are given according to Bowditch's system. Figure 72 is repeated in order that it may be available for direct comparison with the table.

No great weight must be attached to the general agreement which this table seems to show between climatic pulsations and the history of the Mayas. In the first place, the agreement does not apply to details, and in all probability no amount of investigation is ever likely to show that it does so apply. In the second place, so long as Mayan chronology is so uncertain we can not lay much weight upon it. The chief reason for introducing the matter is to point out one of the ways in which the study of climate may cooperate with archeology and history, and each may be used as a check upon the other. In the course of

TABLE 12.

Period.	Date.	Inferred climatic conditions in Maya land.	Historical conditions in Maya land.
1	1000–400 B. C.	Pronounced dry winter season everywhere, strong contrast of seasons, few dense forests, conditions much more stimulating than now.	Period of developing culture and great progress.
2	400–100 B. C.	Similar to (1) but not quite so strong a contrast of seasons.	Period of first known artistic work. Not essentially different from (1).
3	100 B. C.–300 A. D.	Intermediate between (1) and (2), but beginning to become less favorable toward the end of the period, especially in the south.	Period of high culture beginning in the south and progressing northward. By the end of the period great architectural works had ceased in the south but not in the center.
4	300–450 A. D.	Steady increase of unfavorable conditions. The dry season must have largely disappeared in the south and dense forests must have tended to appear whenever cultivation was relaxed	Extinction or great decline of southern civilization. The center of activity moved to northern Yucatan, where it is now located; but there is no evidence of any such state of activity as had formerly prevailed in the south.
5	450–900 A. D.	Highly unfavorable conditions, part of the time no better than those of to-day and at times worse. Forests probably prevailed everywhere except in the narrow strip of northern Yucatan.	The Dark Ages of Maya history. Civilization at a low ebb. No evidence of any great architectural or other activity.
6	900–1100 A. D.	Partial return to favorable conditions of early periods, but not enough to influence the southern part of Maya land.	Pronounced revival of culture, great architectural and other activities, but only in northern Yucatan, that is, in the present dry area and its immediate neighborhood.
7	1100–1300 A. D.	Return to unfavorable conditions about like those of to-day.	Renewed decline of civilization. Frequent wars and invasions. End of the era of building; abandonment of great cities.
8	1300–1450 A. D.	Second partial return to favorable conditions, like (6), but not quite so favorable.	Continued decline of civilization, no evidence of any genuine recovery.
9	1450–1900 A. D.	General continuance of unfavorable conditions.	Persistent continuance of native civilization at a level which is not especially low compared with other lands within the tropics, but is very low and unprogressive compared with the great eras of the past.

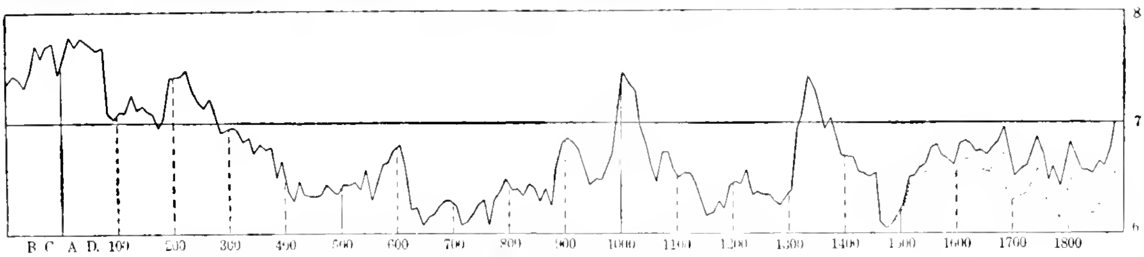


FIG. 72.—Changes of Climate in California for 2,000 Years.
This figure is the same as the part of figure 50 after 100 B. C., but is plotted with a three-fold greater vertical scale.

time, when the ruins of Maya land have been thoroughly explored and excavated, it will doubtless be possible to frame an exact chronology, and to determine the sequence of the main events in Maya history. The doing of this will have no bearing upon conclusions resting on such evidence as the trees in California, but it will prove an admirable test of the portion of our theory involving the relationship of climatic changes to lands within the tropics, and to the history of civilization in that region.

Meanwhile let us sum up the net results of our entire study of climatic changes, whether in Arizona, New Mexico, California, Mexico, Yucatan, or Guatemala. The main significance of the whole matter lies in the fact that from a long and complex chain of reasoning, beginning in Asia and extending to America, we deduce certain consequences, and on comparison with the actual facts we find that on the whole the facts and the consequences essentially agree. The first step in our reasoning was the simple theory that the climate of early historic times was different from that of the present. The second was the further hypothesis that the change from the past to the present has not been regular but pulsatory. This in turn led to the supposition that climatic changes may have been one of the factors which have borne a part in producing certain important historical results. These three steps were taken in Asia and the eastern countries of the Mediterranean basin. The next step was to employ the same methods of research in similar regions of America, with the result that they led to the same general conclusions. Having reached this point, it became necessary to drop the former methods and make an entirely new investigation absolutely unconnected with the preceding steps and wholly independent of the personal opinions of the investigator. This was done by means of the growth of trees. Its results agreed with those of the other methods of investigation in indicating the pulsatory nature of climatic changes. The results also led to two new conclusions. The first was that in continental regions lying in similar latitudes and in similar relation to the sea, climatic pulsations of similar phase occur at the same time both in the eastern and in the western hemispheres. The corollary of this is that all parts of the earth must be subject to climatic changes at the same time, although the nature and degree of the change may vary greatly from place to place. A second conclusion derived from the trees was that climatic changes are due primarily to a strengthening or weakening of the atmospheric circulation, and that their general effect at one extreme is so to weaken the movements of the air that storms are mild and seasonal variations slight. At the other extreme, on the contrary, storms appear to be strong and seasonal variations to be great, because the various climatic zones of the earth are moved far from their ordinary location, especially in winter. Finally, we have taken all our conclusions as to the nature of climatic changes and their relation to historic events and have applied them to a new region in Central America. The result is a considerable degree of agreement between our expectations and the facts, no matter which of our sets of dates is used. If the interpretation of Maya history contained in our table is correct, the agreement becomes truly remarkable. In view of the present uncertainty as to Maya chronology, however, we must once more emphasize the fact that this agreement can not be regarded as proving the accuracy of the various steps leading to our present results, for there are still many points to be investigated. It seems, however, to show clearly that even in this last expansion of our hypothesis we find nothing contrary to it. As we go back toward the earlier parts of the hypothesis each step becomes more and more firmly established. Our main conclusion does not rest upon Maya history, but upon the trees of California and upon hundreds of pieces of evidence in the arid Southwest and in Asia. All these seem strongly to indicate that the climate of the past was different from that of the present and that the change from that time to this has been pulsatory.

CHAPTER XIX.

THE SOLAR HYPOTHESIS.

In the investigation of any scientific problem the natural order of study is: (1) the actual facts, past and present; (2) their causes; (3) their results; (4) the prediction of future events. Thus far in this volume we have been endeavoring to ascertain the actual facts as to the climatic events of the past two or three thousand years. Here and there we have turned aside to a discussion of results as manifested in the topography of the earth, its cover of vegetation, or its human inhabitants, but this has been merely to aid us in ascertaining how far the climate has actually changed. If it be granted that the main conclusions thus far set forth are correct, the way is open to the other three phases of the subject—the study of causes and results, and the prediction of the future. Each of these is so large as to demand a volume to itself. Hence in the following chapters I propose merely to indicate briefly certain facts and relationships which appear to have a bearing upon the cause of climatic changes. I shall discuss an hypothesis which presents a new phase of the old hypotheses of the relation of the climate of the earth to the activity of the sun on the one hand, and to deformation of the earth's crust on the other hand. I do this with full appreciation of the fact that as yet the observational basis of the hypothesis is small. I realize that such an hypothesis is sure to be wrong in certain respects, and may be entirely wrong. I do not present it with any expectation that it will at once be accepted, or that it will supplant other theories. It is offered merely as a first attempt to interpret the theoretical bearing of the new facts set forth in this book. Whatever may be the ultimate fate of the hypothesis, it may, perhaps, at least serve to stimulate the further investigation of the phenomena here discussed and to promote the framing of other and better hypotheses.

Granting the validity of the conclusions set forth in previous chapters, the period from the Pleistocene era to the present has been characterized by a series of climatic changes of highly varying intensity. At one extreme come great changes, such as the glacial period, lasting thousands or perhaps hundreds of thousands of years, and forming some of the most noteworthy phenomena of geological history. At the other extreme come short climatic cycles of various lengths such as 2.5, 11, 21, and 35 years. Few students question the reality of either type of change, although there is much question as to whether they are characterized by any permanent and regular periodicity or whether they occur merely at irregular intervals. Hitherto these two types have commonly been regarded as distinct phenomena, due in all probability to diverse causes. The glacial changes have been supposed to be a completed series of events, which might recur again, but whose causes are not now operative. The minor cycles of the present time, on the other hand, have been generally looked upon either as more or less accidental phenomena due to fortuitous combinations of atmospheric influences, or else as the result of causes which may or may not be connected with the glacial period, but which at least are separated from that period by a pronounced and unbridged gap. This gap appears now to be bridged, and in this fact lies the most important contribution of this volume to our knowledge of the laws of nature. Between the two extreme types of climatic change typified by glacial periods and 11-year cycles, there seem to be two others of intermediate magnitude. First, we have the change by which the climate of the world in general appears now to be different from what it was 2,000 to 3,000 years ago. This change is perhaps of the same degree as the changes of somewhat earlier times which are known as glacial stages. Lastly, the fourth type of climatic change is that which appears so distinctly in the curve of the sequoia. That curve gives strong evidence of distinct climatic cycles measured in units of hundreds of years. So far as we can ascertain, all four of our types of changes, from those of the 11-year period up to glacial epochs, seem to be of essentially the same nature: at one extreme they appear to be characterized by an expansion of the polar zone of climate and a corresponding compression of the remaining zones toward the equator, and at the other by a contraction of the polar zone and a poleward expansion of the others.

The types of changes which have just been mentioned do not embrace all the climatic vicissitudes to which the earth is subject. Back of the minor cycles measured by years or decades, back of the historic cycles measured by centuries, back of the climatic stages measured by millenniums, and back of glacial epochs measured by tens of thousands of years, there lie glacial periods of still vaster dimensions composed of a series of epochs and measured in hundreds of thousands of years. They appear to differ from one another in a way quite unlike that in which one of the smaller epochs or cycles differs from another. During one glacial period the conditions favorable to glaciation may be localized in polar, or at least far northern latitudes, as was the case during the Pleistocene period; while during another the exact reverse may be true, and the glaciation may be localized within from 20° to 40° of the equator, as happened in Permian times. This suggests that while the smaller changes, from glacial epochs down to cycles of a few years, may all be of the same nature, and may be due to the same cause, such pronounced phenomena as the Permian redistribution of the climatic zones as a whole are probably due to another cause. This idea, then, of a twofold cause of the climatic instability of the earth may serve as a guide in our future studies.

In attempting to ascertain the causes of any group of facts two methods may be pursued. In the first place, we may search for phenomena whose effects are beyond the range of observation, but which the processes of reasoning lead us to believe may be associated with the phenomena which we wish to explain. This process has led to two chief climatic hypotheses: one is Croll's theory of the precession of the equinoxes, and the other is the carbonic-acid theory, whose inception we owe to Arrhenius, and which has been so well elaborated by Chamberlain. In developing both theories a long and extremely complicated process of reasoning has been necessary in order to reach a final conclusion. It has been impossible, even on a small scale, to test most of the steps involved in the reasoning.

The other method is the discovery of phenomena which can actually be seen to vary in harmony with the facts which we desire to explain. This method has also given rise to two climatic theories. In the first place, it is evident to the most unskilled observer that the extent, elevation, and relief of the land are of the highest importance in causing differences in climate. From this has arisen the theory that the chief changes in the climate of the earth are due to variations in the location, form, and extent of the continents, accompanied by corresponding changes in the circulation of the air and of oceanic waters. In the second place, no one doubts that the amount of energy received from the sun is the fundamental factor in determining the climate of the different parts of the world. If the amount of radiation received from the sun should change appreciably, the climate of the earth would certainly be modified. From this has arisen the solar theory. The two methods of investigation which have just been indicated must in practise be carried on together; nevertheless, there is a distinct and important difference. A highly theoretical conception, such as the precession of the equinoxes or the abstraction of carbon dioxide from the atmosphere, is more liable to error than is an observational conception, such as the climatic effect of the altitude and form of the lands, or the effect of changes in solar radiation upon terrestrial temperature.

The four theories which have just been mentioned, with their appropriate modifications, are the only ones which have hitherto had any permanent standing as attempts to explain glaciation or the other climatic vicissitudes of geological times. The precession theory seems to have been thoroughly tested and found wanting. It demands a rigid periodicity which ought to cause the recurrence of the same phenomena repeatedly at precisely the same intervals. Possibly precession may account for slight climatic variations, but the larger changes fail entirely to meet its requirements. The three other theories—that is, those of carbonic acid, elevation of the lands, and solar changes—may be considered as standing at the present time upon an equal footing. It is incumbent upon us now to test them in the light of the new knowledge which seems to have come from the study of the climate of historic times.

The outstanding fact to which our investigations seem to lead is that at the present time the climate of the world is highly unstable. Contrary to the old idea of uniformity, we find, apparently, that cycles, large and small, are continually in progress. So far as our present knowledge goes, it is impossible to differentiate between the larger and the smaller except in the matter of size. If this is so, it seems essential that an acceptable theory should explain not only the great changes but the small ones. In other words, if we omit for the moment the great phenomena of the redistribution of the climatic zones of the earth as a whole, and consider only glacial epochs and smaller phenomena, the causes of climatic variations must apparently be capable not only of large, slow changes, but also of those which are small and rapid. A cause must be found to explain long cycles, such as the glacial and interglacial epochs of the Pleistocene period, and that same cause or some other must also be of such a nature that in the space of half a century it can produce a change as great as that which apparently occurred between 1300 and 1350 A. D. At this point both the theory of elevation and that of carbon dioxide seem to break down. It seems as if neither the altitude of the mountains and continents of the world, nor yet the amount of carbon dioxide in the air can, almost in our own day, have changed so quickly and markedly as to cause an epoch such as that which seems to have culminated in the fourteenth century.

Moreover, throughout geological time there is good reason to think that minor changes of climate are of much more frequent occurrence than is commonly supposed. I have discussed this matter in an article upon "Characteristics of the Glacial Period in Non-glaciated Regions,"* and shall not dwell on it here. The work of Gilbert upon limestones, and the fuller work of Barrell upon sedimentation, seem to indicate the constant succession of minor climatic fluctuations during a large portion of geological time. These, too, must be explained by any complete climatic theory.

Finally, we may add that so far as any absolute measurements have been made, we have no definite evidence of variations in climatic conditions corresponding to any observed change in the altitude of the earth's surface or in the amount of carbon dioxide in the air. Therefore we may say that so far as the small climatic changes are concerned, it is hard to conceive of their having arisen in accordance with either of these two theories. This by no means must be taken as implying that changes both in the composition of the air, and far more in the altitude and position of the land, have not had most pronounced effects. It merely means that they appear to be of importance chiefly in reference to long-continued, slow changes, but fail when an attempt is made to use them in explanation of anything except major phenomena of long endurance.

At this point we must raise the query whether purely meteorological causes now in operation may not suffice to account for minor climatic changes. The varying conditions of the seasons, the accidental accumulation of masses of clouds, the fortuitous convergence of an unusual number of storms, the heating of a portion of the earth's surface by lava,

* Bulletin of the Geological Society of America, vol. 18, 1907, pp. 351–388.

the temporary filling of the air with dust from volcanoes, and the cooling of parts of the ocean by an unusual number of icebergs are a few of the many agencies which combine to cause the weather of one year to differ from that of another. It is not only conceivable, but highly probable, that these agencies account for a large share of the variations which are visible within an ordinary human lifetime. Many meteorologists of the highest standing regard them as a sufficient explanation of all changes since the end of the glacial period. These meteorologists, however, assume a definite end of the glacial period, and their theory was framed before the trees of California had disclosed such strong evidence of post-glacial and, especially, of historic fluctuations.

Unfortunately it is impossible to disprove or prove their view. At the present time we are only beginning to determine whether the difference between the weather of one year and another is due solely to meteorological causes, such as are mentioned above, or partly to them and partly to solar or other unknown agencies. The most that we can do is to consider the probabilities, and they are bound to seem different to different observers. The earth's atmosphere is extremely sensitive and mobile. The slightest change in temperature, pressure, or other conditions sets it in motion. Because of this mobility, however, there is an equally prompt tendency to correct any departure from equilibrium as quickly as it is formed. In summer the full development of the great areas of continental low pressure, and of the accompanying monsoons or other in-blowing winds, reaches its full development only about a month after the sun reaches its most northern point. Therefore it would seem as if any accidental departures of the earth's climate due to purely meteorological causes must speedily reach their limit, and then disappear as the atmosphere attempts to regain its equilibrium. So long as we knew of no climatic changes between those of 35-year cycles and those of glacial epochs, the purely meteorological explanation of present phenomena was commonly accepted as sufficient. The changes indicated by the California trees, however, seem to put a strain on this explanation. They appear to demand not only that something should have caused changes which seem to be of as great intensity as those which now differentiate one year from another, but that the atmosphere, in spite of its instability, should have been held for a century or two at one or the other of these extremes. This may be possible, but in many ways it seems improbable. Some other cause seems needed thus to change the condition of the atmosphere and then prevent it from swinging back to its old state of equilibrium.

Coming now to the sun as a possible cause of climatic variations both large and small, the case is quite different. The solar hypothesis is not confronted by the same difficulties as any of the others. From the work of Abbott, Fowle, and others we know, as a matter of observation, that the radiation of the sun varies to a degree which is easily measurable with the pyrheliometer, but the variation is quite irregular in duration and still more so in amplitude, some maxima being several times as important as others. The difficulty with the solar theory is that it is avowedly indefinite. The sun has indeed been proved to be a variable star, but the observed variations are of only slight magnitude and duration. We can, of course, assume that in the past it has varied on a larger scale than at present, but no one has yet been able to point to more than the most shadowy indications that this is the case. Moreover, meteorologists are not as yet wholly agreed as to what would be the effect of an increase in the intensity of the sun's radiation. Some think that it would simply warm the earth and produce a mild climate, the change being especially marked far toward the poles. Others think that its effect would be felt chiefly at the equator, and that thereby the circulation of the atmosphere would be so accelerated and cloudiness in non-equatorial regions would be so increased as to bring on glaciation.

Without attempting to discuss this matter, let us briefly see what ground there is for thinking that present changes in the intensity of the sun's radiation are actually connected with present variations of climate. In the first place, it is almost universally agreed that there is a very direct and close connection between the sun-spot period and the various magnetic phenomena of the earth. It is possible that these magnetic phenomena are intimately connected with our cyclonic storms or other climatic factors, but little is known about this and we can not here discuss it. As to the general relation of sun-spots to the common climatic elements of temperature, pressure, winds, precipitation, and the like, the matter may well be summed up in the words of Hann, the great modern authority on climate:*

"The results of very numerous and complex investigations of the connection of the sun-spot period with variations of the meteorological elements have not wholly corresponded to expectations. The influence of the sun-spots on the meteorological elements has been proved as comparatively unimportant. Only in the most favorable cases is one in the position to consider that the traces of a parallel course in the progress of certain meteorological elements and in that of the sun-spot frequency is proven. There can be no thought of the prediction of the course of the weather on the ground of the sun-spot cycle."

From this broad general statement Hann goes on to show that the amount of agreement between sun-spots and climatic phenomena varies greatly according to the part of the earth and the precise climatic elements which are investigated. In general, temperature is the element which shows the closest agreement with solar changes, and this applies much more to equatorial than to other regions. To quote Hann once more (p. 356):

" For the best-grounded demonstration of a sun-spot period in the mean annual temperature of the various regions of the earth our thanks are due to Köppen.† In the tropics the parallelism of changes in the mean annual temperature and of the frequency of spots on the sun is comparatively well proved, in middle and higher latitudes less well. The mean amplitude of the changes in the annual temperature from a sun-spot minimum to a maximum amounts within the tropics to 0.75° C., and beyond the tropics to 0.54° C. The course of the phenomena within the tropics appears from the following numbers, which show the departure of the yearly mean temperature from the mean for a long period.

TABLE 13.—*Sun-spot Periods in the Yearly Mean of Temperature within the Tropics.*

Sun-spot minimum	+ 0.33°	Sun-spot maximum	− 0.32°
1 year after minimum	+ 0.15	1 year after maximum	− 0.27
2 years after minimum	− 0.04	2 years after maximum	− 0.14
3 years after minimum	− 0.21	3 years after maximum	+ 0.08
4 years after minimum	− 0.28	4 years after maximum	+ 0.30
		5 years after maximum	+ 0.41 "

The maximum of temperature falls about 0.9 year before the sun-spot minimum, while the minimum of temperature practically coincides with the maximum of the spots.

As to the other climatic elements, the case is by no means so clear, and the results sometimes appear to be contradictory. The reader who would carry the matter further is referred to the last chapter of volume 1 of Hann's Klimatologie, and to the large number of references there cited. In general it appears that the strongest evidence of a sun-spot cycle in climate is found when a single element, such as summer rains or tropical cyclones, to take the two best examples, is considered alone, and when it is investigated by the use of means for a large number of stations and for long periods. When single stations or single sun-spot cycles are considered there is likely to be no visible relation whatever. In rainfall, as in temperature, there is decidedly more evidence of a sun-spot cycle within the tropics than in other parts of the world. One of the most noticeable cases and one of the few which is distinct and unmistakable is found in the number of tropical cyclones or hurricanes both in the Indian Ocean as investigated by Meldrum and in the Atlantic according to Poey.‡

* J. Hann, Handbuch der Klimatologie, Stuttgart, 1908, vol. 1, pp. 355–356.
† W. Köppen, Über mehrjahrige Perioden der Witterung in besondere über die 11-jährige Periods der Temperature.
‡ See Hann, Klimatologie, vol. 1, p. 360.

In both cases the number and intensity of cyclones increase and decrease in harmony with those of sun-spots, the greatest number occurring at the time of maximum spots, which appears also to be the time of minimum temperature. Wolf has compared the frequency of the cyclones with the number of sun-spots and gets the interesting result seen in table 14.

Table 14.

No. of cyclones per year.	Relative sun-spot numbers.
1 and 2	17
3	59
4	62
5	70
6 and 7	80
8	88

Here we seem to have an unmistakable relationship; but when other climatic elements are investigated, for instance, thunderstorms, hail, movements of glaciers and the like, and especially when regions far from the equator are considered, the indications of a sun-spot cycle become so weak and conflicting that no true causal connection has yet been established.*

In view of the importance and complexity of this subject it seems advisable to test it by means of our measurements of the growth of trees. This is especially desirable because, although the trees in some respects fail to give a perfect record, their record has the great advantage of being long and homogeneous. Professor Douglass has already made a beginning in this subject. From the trees of Arizona he has found an apparent agreement between the amount of growth and the sun-spot cycle. The average 11-year cycle for a long period seems to show a double maximum in the growth of trees. Inasmuch, however, as an arbitrary period of 11.4 years was used and no attention was paid to the fact that the actual sun-spot cycle may range from 7 to 16 years, it is questionable whether much reliance can be placed on these results.

The other method of Professor Douglass, on the contrary, is reliable and conclusive. In figure 25, page 120, he has simply compared the growth of 13 trees in Germany since 1820 with the standard sun-spot curve. The result is striking. Each curve shows seven major maxima, and of these seven all but one occur at essentially the same time in both curves. In the one exceptional case, the trees reach a maximum in 1901, while the sun-spots do not reach their highest point till four years later. In view of the accidents to which trees are liable and the extent to which the failure of the rains in one or two critical months may check growth for several years, one single disagreement out of seven possible agreements is no more than we should expect. The apparent relation between sun-spots and tree growth thus found in Germany is especially significant because the German curves of temperature and rainfall do not agree so closely with the sun-spots. This seems to indicate that when temperature, total rainfall, and seasonal distribution of rainfall are all integrated, as they are by the growth of the trees, the sun-spot cycle is more evident than when individual climatic elements are concerned. This appears to be the reverse of what is true in equatorial regions.*

A test of the trees of California in this same fashion fails to show any such agreement with sun-spots as is found in Germany. In the two curves of figure 75 a resemblance may be traced at certain points, but it soon gives way to disagreement and appears to be purely accidental. So far as these particular curves are concerned there seems to be no warrant for believing in any connection between solar changes and climate. The contrast in this respect between the German and California curves is a good illustration of the complexities and apparent contradictions of this involved subject. We shall later inquire whether such apparent inconsistency is incompatible with a solar theory of climate or is its expectable consequence. Meanwhile let us investigate the same subject by another method.

The method here employed is simply to determine the average rate of growth at different portions of the actual sun-spot cycle, and see whether it varies in harmony with the cycle. Beginning with 1610 A. D., when the dates of maximum and minimum sun-spots first begin to be known with certainty, each sun-spot cycle has been taken by itself and divided into parts according to table 15.

* See notes on pp. 205 and 253.

TABLE 15.

1. The year of maximum spots.	6. One year before minimum.
2. The year after maximum.	7. The year of minimum spots.
3. Two years after maximum.	8. One year after minimum.
4. An intermediate period of decreasing spots having an average length of about 1.5 years.	9. An intermediate period of increasing spots having an average length of about 1.5 years.
5. Two years before minimum.	10. Two years before maximum.
	11. One year before maximum.

In order to have two separate sets of data for comparison, the period since 1610 is divided into two parts, 1610–1754, and 1755–1900, each consisting of 13 complete sun-spot cycles. The two parts differ in respect to the length of time from maximum to minimum. In the earlier period the average lapse of time from maximum to minimum was approximately the same as from minimum back to maximum, or about 5.5 years in each case.

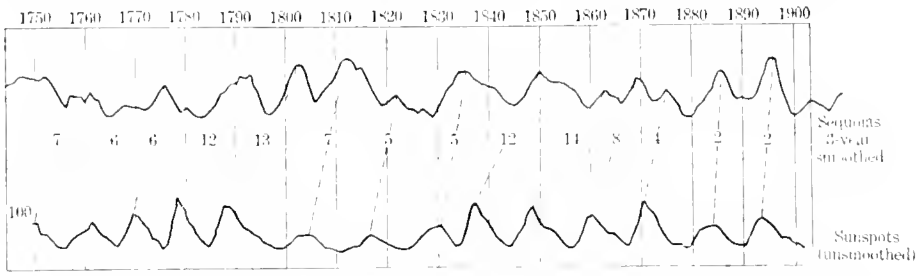


FIG. 75.—The Relation of Sun-spots and Tree Growth in the 11-year Cycle.

In the later period the time from maximum to minimum was not far from 6.5 years, while that from minimum back to maximum was 4.5. Hence in the first period it was necessary to omit No. 3 in table 15, and in the second period to omit No. 10, thus in each case leaving the sun-spot cycle divided into ten parts, eight of which have a length of a year, and two of 1.5 years. For each of these ten parts I have computed the average growth of eleven sequoia trees, the only ones whose yearly growth it has yet been possible to measure back to 1610 A. D. with sufficient accuracy. The results are shown in figure 76.

In order to test the matter in a somewhat similar way in Europe I have computed the average price of wheat in England according to the tables of Thorold Rogers, using the same ten divisions of each sun-spot cycle. The use of these tables was suggested by A. H. Swinton, Esq., of Totnes, England, who has devoted much time to a careful study of the relation of sun-spots and weather. During the period from 1610 to 1754 England produced her own food supply, economic conditions did not change greatly, and there were no protracted or highly devastating wars. Accordingly the main factor in determining variations in the price of wheat was the amount actually raised in the country itself; and that, of course, was dependent chiefly upon variations in the weather from year to year, dry years being in general favorable so that prices were low, and wet years unfavorable so that prices were high. During the later period, 1755 to 1900, the Napoleonic wars, the growth of manufactures, the importation of food from America, and changes in the tariff have completely altered the conditions of British agriculture, so that the price of wheat no longer depends upon the amount raised locally. Hence it is not possible to use this later period.

Thus in figure 76 we have three curves, H and I on the left for the period from 1610 to 1754, and I′ on the right for 1754–1900. Above these the sun-spot curves, G and G′, have been placed, G being merely an estimated curve, since exact data are not available, while G′ is the mean of the actual observations as given by Wolf. In using data derived from sources such as the growth of trees and the price of wheat it is obvious that there is a large opportunity for error, partly from mistakes in actual observation, but chiefly because of the many non-climatic accidents to which vegetation and prices are both liable. This error can not be wholly eliminated. Its effect, however, is reduced by the fact that each point in the unsmoothed curves, the dotted lines in figure 76, represents the average condition at that particular phase of 13 cycles. Moreover, the values for each cycle are in turn the average of a considerable number of records in the case of the price of wheat and of 18 measurements along the radii of 11 trees in the other case. In order still further to eliminate accidents I have drawn the solid lines which represent the results of smoothing by the use of 3-year means. For instance, the year before minimum, the year of minimum,

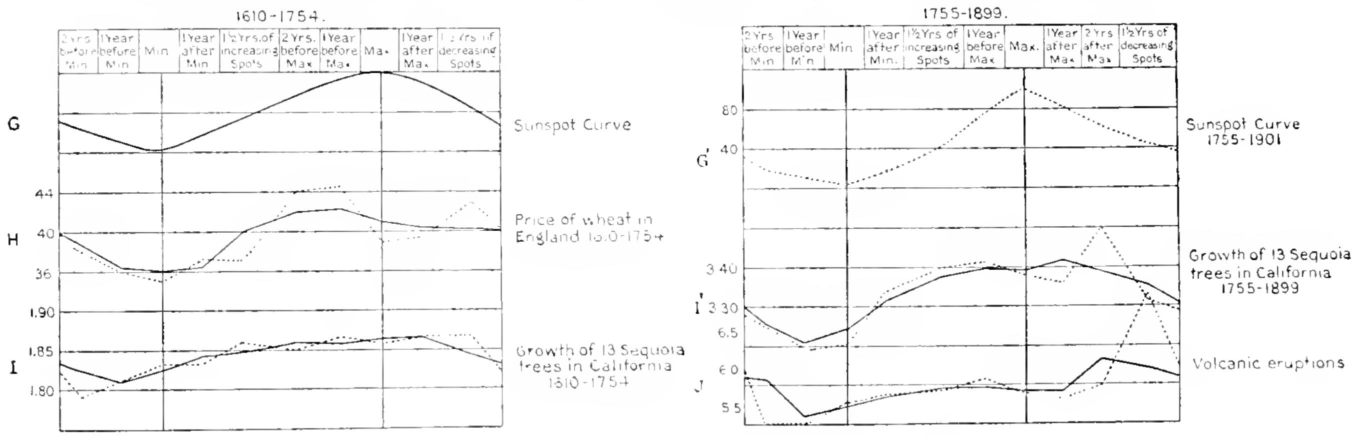


FIG. 76.—The Sun-spot Cycle and Terrestrial Phenomena.

and the year after minimum have been averaged, and the result plotted in the minimum year. Thus in general each point in the smoothed curve of tree growth is the average of 18 by 13 by 3, or 702 measurements. With so large a basis of facts it seems probable that accidental errors have been largely eliminated. The remaining departures of the curves from straight lines would seem to indicate some permanently variable factor which varies in harmony with the sun-spot cycles and for that reason will not disappear even when a large body of data is averaged. Aside from climate there appears to be no known factor which could vary in such a way as to have the same periodicity as sun-spots and yet cause the rate of growth of vegetation to fluctuate.

Taking the solid lines G, H, I, and I′ and the dotted line G′ in figure 76 we see that they are in substantial agreement. The curve of prices is at a minimum at the time of the sun-spot minimum, and reaches a maximum a year before that of the solar curve. Its highest point is nearly 25 per cent higher than the lowest. The curve of the sequoias for the earlier period is at a minimum a year before the sun-spots and at a maximum a year later than the spots. The difference in this case is only 4 per cent, but the change from minimum to maximum, even in the unsmoothed curve, is so regular that it seems as if it must be due to a genuine difference in the amount of rain at different portions of the sun-spot cycle. The fact that the sequoia curve for the second period, I′, presents almost the same appearance lends color to this conclusion, more especially as the difference between maximum and minimum is here about 10 per cent. Such an agreement among phenomena occurring in two distinct periods in regions far remote from one another is important, since it adds another to the many lines of evidence which suggest, though they do not prove, a connection between the solar cycle and terrestrial climate. It also points to the probability that in extra-tropical regions climatic records extending over a long period may disclose a cycle which is completely masked by the minor variations which take place from year to year.

Without attempting to press this point further, let us see exactly what our curves appear to indicate. The curve of the price of wheat has its maximum a year before the solar maximum. Inasmuch as the price of grain responds quickly to variations in the crop, it seems fair to suppose that the maximum price would, on an average, be reached within a year after the minimum crop was harvested. The worst crops in England are those of the wettest years when the ground is waterlogged and there is scanty sunshine. Hence we may infer that in the period from 1610 to 1754 A. D. the maximum rainfall in England occurred on an average one or two years before the time of maximum sun-spots. In studying the sequoias of California we found that the maximum growth comes on an average about two years after the maximum rainfall. In the curves before us the maximum of the unsmoothed curve for the first period comes two years after the sun-spot maximum, and that of the smoothed curve one year. In the later period the same relation is observed. Subtracting two years from the time of maximum growth, we find that the probable time of maximum rainfall in California is a year or less before the sun-spot maximum, a result which agrees closely with that obtained in England and suggests that these two regions in the western parts of two great continents fare somewhat similarly, so far at least as winter rains are concerned. This agrees with the conclusion derived from our curves of changes of climate in America and Asia for the past 2,000 or 3,000 years. When minor fluctuations are eliminated, times of heavy precipitation in the corresponding parts of the eastern hemisphere and of America seem approximately to coincide.

The chief objections to the theory of an 11-year climatic cycle due to sun-spots are two. In the first place, while it must apparently be granted that the earth's temperature actually varies in harmony with the spots of the sun, the variation is so slight that many of the highest authorities consider it too small to have an appreciable effect. In the second place, while the various meteorological elements, especially rainfall and tropical cyclones, show some indications of a cycle corresponding with that of the sun, the evidence of this is thus far largely confined to the region within the tropics. Even there, and still more in other places, curious contradictions are noticed. Let us examine each of these objections in detail.

Our consideration of the objection that changes in the amount of heat received from the sun are insufficient to cause appreciable meteorological phenomena may well center on an article by Newcomb.* This article is so important that its appearance, together with that of a similar article by Bigelow, led Hann to add an appendix to the first volume of his "Klimatologie" after the main volume was finished.

Newcomb's study of the relation of the temperature of the sun to that of the earth is the most comprehensive and accurate that has yet been made. His conclusions are so careful and conservative that they can scarcely be doubted so far as they are based directly upon statistics. He expresses himself thus (p. 379):

"A study of the annual departures [from mean temperature] over many regions of the globe in equatorial and middle latitudes shows consistently a fluctuation corresponding with that of the solar spots. The maximum fluctuation in the general average is 0.13° C. on each side of the mean for the tropical regions. [The maximum temperature coming at times of minimum sun-spots.] The entire amplitude of the change is therefore 0.26° C. [0.47° F.], or somewhat less than half a degree of the Fahrenheit scale."

On an earlier page (341) he says:

"Although the reality of this 11-year fluctuation [both solar and terrestrial] seems to be placed beyond serious doubt, the amplitude being several times its probable error, its amount is too small to produce any important direct effect upon meteorological phenomena."

Again, on page 384, he puts in italics the last part of the following quotation:

"It follows as the final result of the present investigation that *all the ordinary phenomena of temperature, rainfall, and winds are due to purely terrestrial causes, and that no changes occur in the sun's radiation which have any influence upon them.*"

* A Search for Fluctuations in the Sun's Thermal Radiation through their Influence on Terrestrial Temperature, by Simon Newcomb. Trans. Am. Phil. Soc. U. S., vol. 21, v, 1908.

While Newcomb's conclusion as to the change of temperature between the times of maximum and minimum sun-spots rests upon unassailable evidence, his last conclusion as to the relation of the changes to meteorological phenomena is based purely on inference and is open to question. He has failed to consider the effect which even a slight change of temperature may have upon meteorological conditions provided it be permanent. In his 11-year cycle the range of temperature is 0.26° C. In order to estimate the true importance of such a variation, it is necessary to consider what would be the result if the temperature no longer fluctuated back and forth between the two extremes every eleven years, but remained constant at one extreme for a few centuries and then at the other for a corresponding length of time.

In order to explain the glacial period, geologists and students of "paleo-meteorology" postulate a change of the mean temperature of the earth's atmosphere many times larger than Newcomb's change in the 11-year cycle, but not of a different order of magnitude. Penck, the leading German student of glaciation, believes that a permanent change of 5° C. is sufficient to account for the difference between the conditions of the glacial period and those of to-day. According to Ekholm, a lowering of the mean annual temperature to the extent of from 7° to 9° C. would cause the snow-line of the earth as a whole to descend 3,300 feet, and would lead to a revival of the glacial period. Bonney thinks that during the glacial period the temperature of England was about 20° F. lower than it now is, and the mean temperature of the earth's atmosphere as a whole was from 15° to 20° F. lower than at present. Brückner states that a lowering of the earth's temperature to the extent of 3° or 4° C. would probably suffice to account for the phenomena of the glacial period. He considers that the change in temperature would be relatively slight in equatorial regions and great in polar regions. Finally, David, from a study of glaciation in Australia and other less familiar parts of the world, arrives at the conclusion that in order to explain the phenomena of the last great advance of the ice it must be assumed that the temperature of that time was lower than that of the present by "probably not less than 5° C."

The average value of the decrease in temperature necessary to produce a glacial period, according to the statements of the five authorities cited above, amounts to from 5° to 6° C. That is, they conclude that if the mean temperature of the earth were to fall 5° or 6° C., and were to remain thus low for a sufficient length of time, meteorological conditions would be so altered that a large part of North America would be shrouded with ice down to about the fortieth degree of latitude, and Europe would suffer a corresponding glaciation. If a change of from 5° to 6° C. would produce such a result, it seems reasonable to suppose that the change of 0.26° C. which Newcomb has determined in the eleven-year sun-spot cycle would produce a corresponding result on a smaller scale, provided the duration of the period of low temperature were long enough. To take a specific case for illustration, the Rhone glacier is now barely 6 miles long; the foot of the ice stands at a height of 5,780 feet above sea-level and the surface of the ice at its origin is 10,200 feet above the sea. During the period of maximum glaciation the glacier was 240 miles longer than it now is; its foot stood about 4,700 feet lower than is now the case, and its surface near the origin was 1,400 feet above the present surface.

For the sake of conservatism, let it be assumed that the change of temperature which, together with corresponding changes in winds and precipitation, was necessary to cause the Rhone glacier to assume its former great dimensions was 13° C., which is greater than the maximum figure given above (Bonney's, 20° F., or 11.1° C.), and more than twice the mean of the five authorities cited. Then a change of 0.26° C. would be one-fiftieth of the change necessary to cause the Rhone glacier to assume the dimensions which it had during the glacial period. It seems fair to assume that the results of a small change of climate would be approximately proportional to those of a larger change. If this is so, the difference of 0.26° C., which Newcomb finds between the mean temperature of periods of minimum sun-spots and those of maximum sun-spots, would cause pronounced changes in the Rhone glacier, provided the low temperature lasted long enough to allow of the abundant accumulation of snow. In that case, if the form of its valley were favorable, the Rhone glacier might become 5 miles longer than it now is; or, if the gradient of the valley bottom be assumed as uniform, the ice might descend 90 feet below its present level; or the glacier might increase 28 feet in thickness. The exact nature of the change in the glacier and its exact dimensions would depend upon the topography of the Rhone Valley and upon the relation of precipitation to temperature, winds, and other meteorological phenomena, but the figures which have just been given show the order of magnitude of the results which might be expected from a lowering of the mean annual temperature of the earth to the extent of 0.26° C., provided always that the change were permanent rather than temporary. A change of temperature capable of producing such results, or even results half as great, would scarcely seem to be too small to produce "any important effect upon meteorological phenomena." The truth of Newcomb's conclusions appears to be at least an open question.

Let us turn now to the other great objection to the theory of an eleven-year climatic cycle due to the sun: Regions within the tropics may show fairly strong indications of such a cycle, but even there a certain number of apparent contradictions are found, while as higher latitudes are gained the indications appear to become much less distinct and more contradictory. Is such a state of affairs consistent with the theory of the climatic influence of sun-spots? At first sight one is inclined to answer with a categorical negative, but the recent meteorological investigations of Arctowski oblige us to reconsider the matter. By a patient sifting of a vast mass of figures he has shown that both in Europe and America there appear to be areas of abnormal pressure, temperature, rainfall, and the like, which persist for several years and move irregularly backward and forward.* His conclusions are based partly on direct meteorological records and partly upon statistics of the growth of wheat or corn. His method can best be described by means of specific examples. Taking as a standard the mean temperature of the various portions of the United States or Europe, Arctowski has computed the departure of each station from the normal. At first he did this by years, but in his later work, which is not yet published, by months. The results are striking. He finds that the regions where the mean temperature for the given period is above or below the normal are not distributed irregularly but with much system. He does not find one region showing excess while its immediate neighbor shows deficiency, and the one beyond that again excess. On the contrary, the excess of temperature is greatest at one particular point; from there it decreases gradually until the area of normal temperature is reached, beyond which the excess gives place to deficiency, which in turn centers around a definite spot. The degree of regularity is such that lines of equal excess or deficiency can be drawn in the same fashion as isotherms. These present almost the appearance of the isobars of a barometric map, as is illustrated in figures 77 to 80. These particular maps represent the corn crop, but maps of temperature, pressure, or the growth of other crops would have the same general appearance, although the areas of excess or deficiency would be different in each case. The areas which are above the normal in temperature have been termed "pleions" by Arctowski, and those below normal "anti-pleions," those above or below the normal in pressure are called areas of "hyper-pressure" and of "hypo-pressure," while places having an excess or deficiency of crops are designated "fats" and "leans." For the sake of convenience, however, I shall depart somewhat from his usage, and shall speak of all areas of excess as pleions and all areas of deficiency as anti-pleions. Thus we may have a pleion of temperature, crops, or pressure, and the three may be quite unrelated to one another. In the year 1901 it will be seen that so

* Bulletin American Geographical Society, vol. 42, 1910, pp. 270 and 481; vol. 44, 1912, pp. 598 and 745; vol. 45, 1913, pp. 117–131. L'enchaînement des variations climatiques, Bruxelles, 1909.

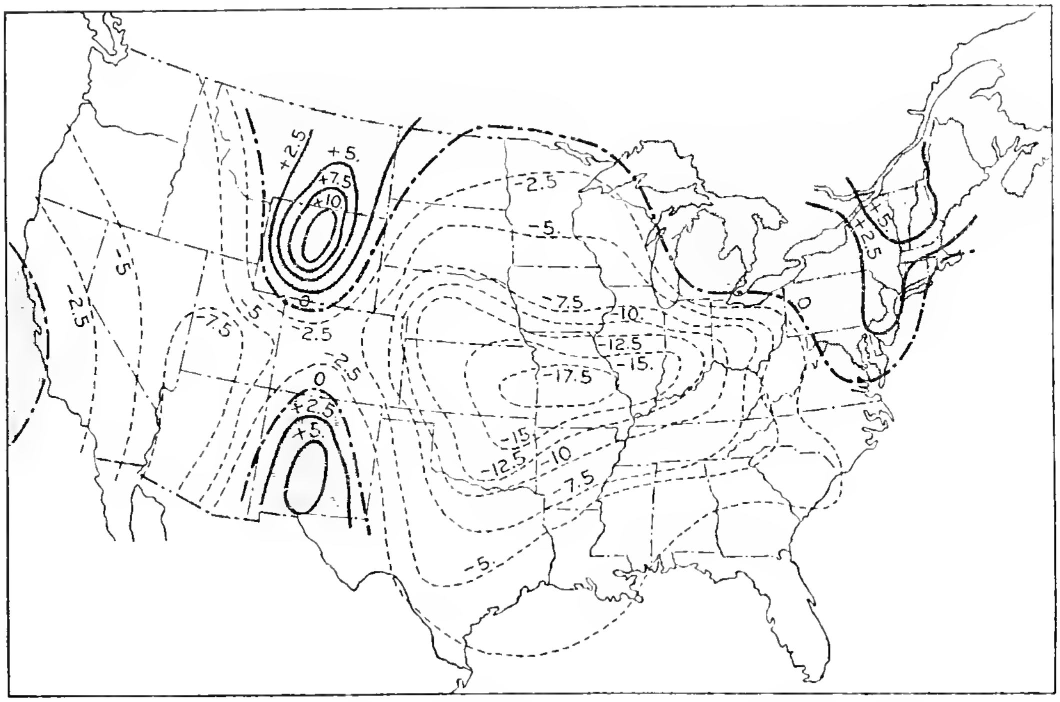


Fig. 77. The Corn Crop of the United States, 1901, a "Lean" Year, after Arctowski.

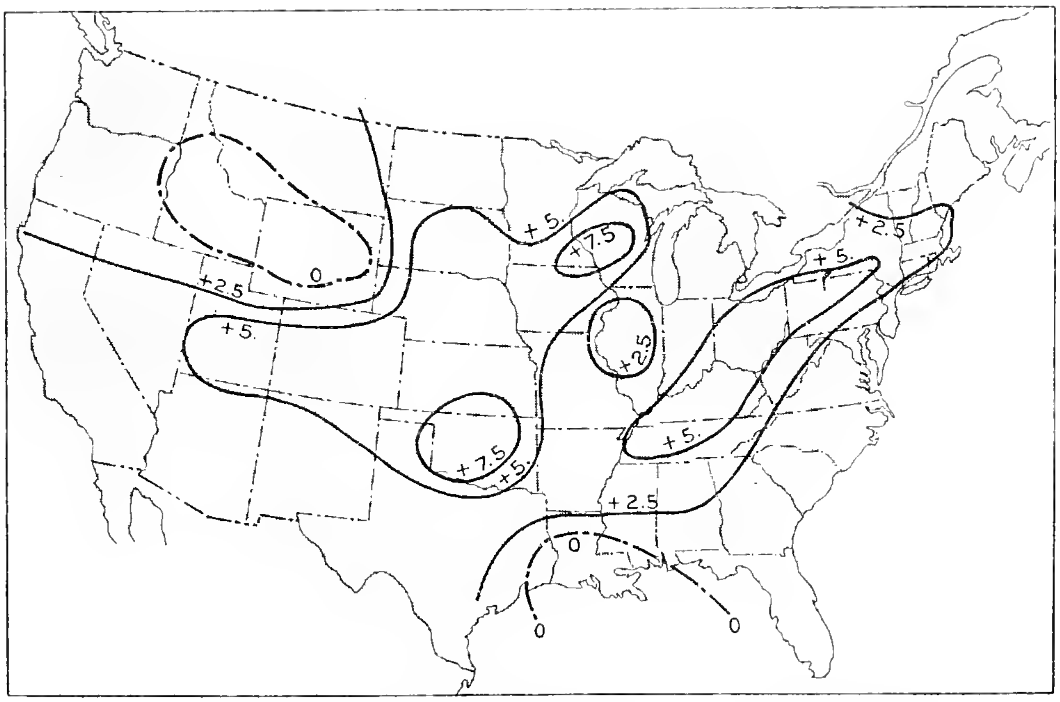


Fig. 78.—The Corn Crop of the United States, 1906, a "Fat" Year, after Arctowski.

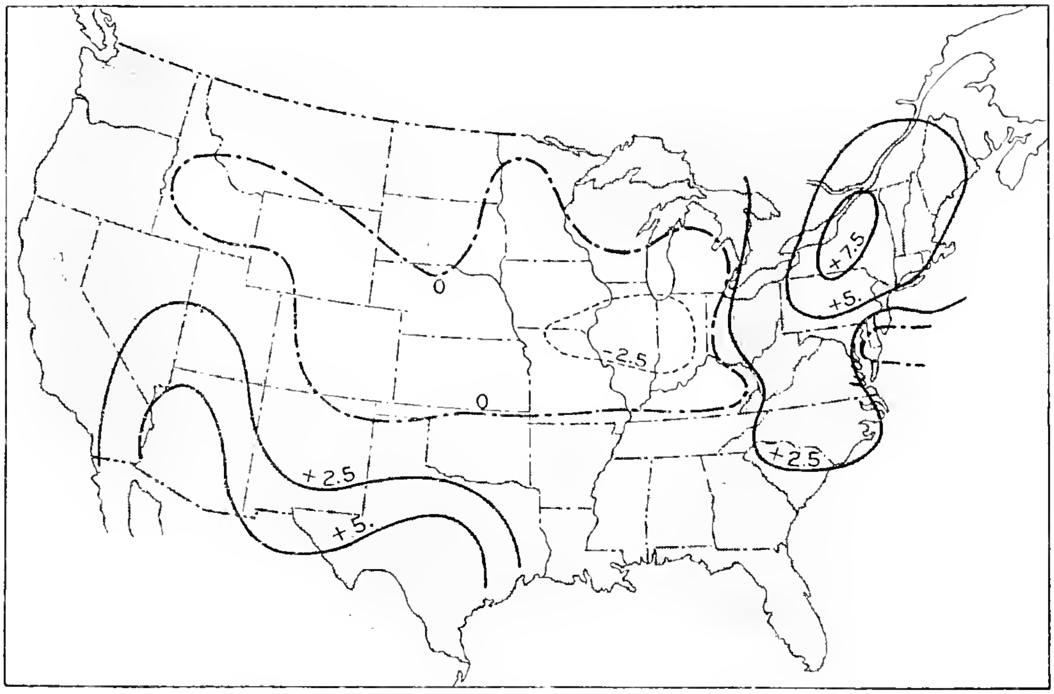


FIG. 79.—The Corn Crop of the United States, 1908, after Arctowski.

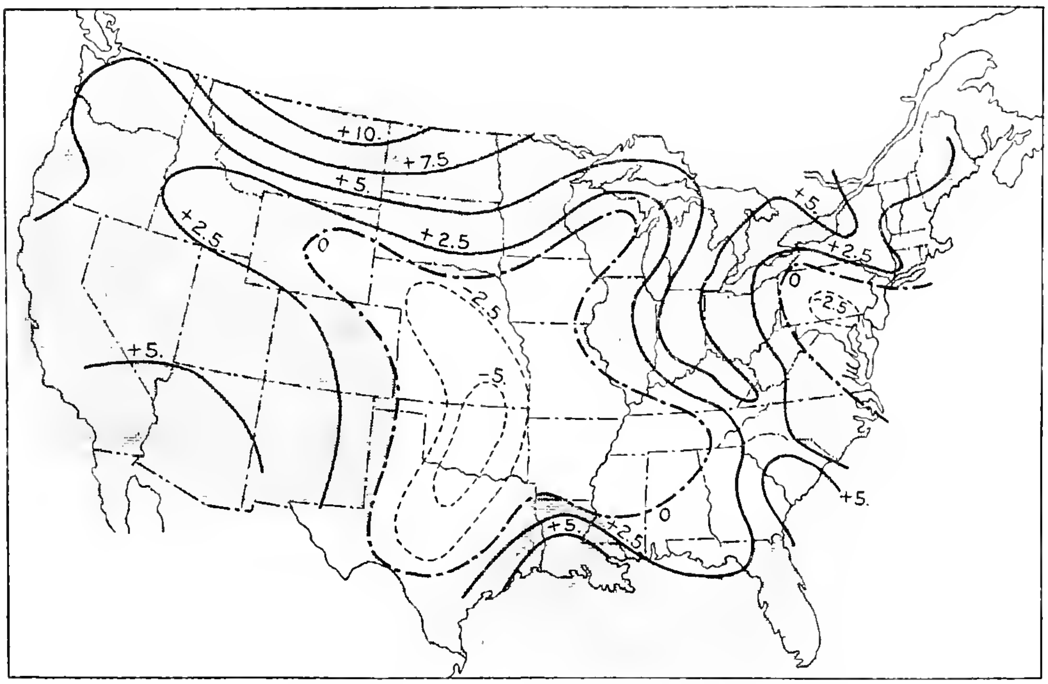


FIG. 80.—The Corn Crop of the United States, 1909, after Arctowski.

far as the production of corn was concerned, extremely anti-pleionic or "lean" conditions prevailed over most of the United States, which means that there was an especial deficiency in the rains of June and July. In 1906, on the contrary, only one small area was lean, and even there the deficiency was less than 2.5 bushels per acre. Throughout all the rest of the country "fat" conditions prevailed—that is, the crop was better than the average.

Figures 79 and 80, for the years 1908 and 1909, illustrate an interesting feature of the pleions and anti-pleions of all sorts of meteorological phenomena, namely, their persistence from year to year in spite of certain changes in form and location. The large anti-pleion in the center of the United States in 1908 has contracted in its east-and-west dimensions and has moved south in 1909, but it is clearly recognizable. In similar fashion the minute anti-pleion over Delaware in 1908 has expanded over New Jersey, Pennsylvania, Maryland, and part of Virginia in 1909.

This emphasizes a most characteristic and important feature of the pleions and anti-pleions—that is, their movability. By means of a series of monthly charts based on overlapping means for 12 months and thus eliminating all variations due merely to the succession of the seasons, Arctowski has discovered that a given pleion may last for many years, during which its center moves back and forth in irregular curves whose north-and-south component apparently exceeds the east-and-west. Sometimes they grow weak and tend to divide into two or more sections, and practically disappear, while again they strengthen and gather into strongly localized areas of pronounced intensity. Just where they originate or how they disappear is not yet clear, but apparently they do not often pass from the sea to the land. This much, however, is certain: they are a pronounced feature of continental and perhaps of oceanic climates, and deserve most careful study, since in them may lie the key to the prediction of the character of a season—months or even a year or two beforehand.

For our present purpose another phase of Arctowski's study of pleions and anti-pleions is particularly important. In his article on Arequipa* he shows that the 44 values of the "solar constant" as measured by Abbott and Fowle between October 9, 1902, and May 14, 1907, agree in general with the departures of the mean monthly temperature from the normal at Arequipa. This appears in figure 81, where the upper curve shows the changes of the solar constant in calories and the lower the departures of atmospheric temperature at Arequipa. To quote Arctowski:

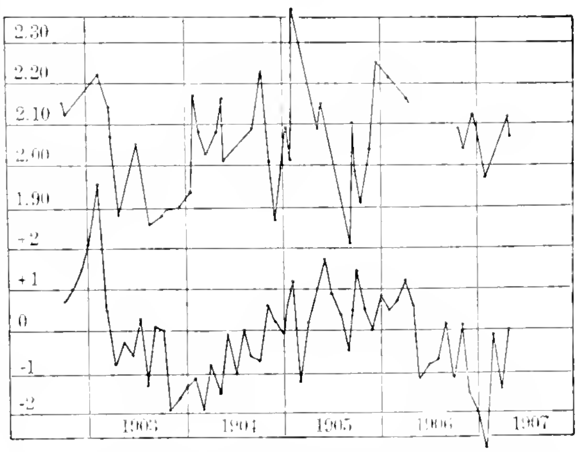


Fig. 81.—Variations of Solar Constant (upper line) and Monthly Departures from Mean Temperature at Arequipa (lower line), after Arctowski.

"It is obvious that the number of observations of the 'solar constant' is insufficient to show all the details of the variation. Moreover, some measurements may have been taken precisely on exceptional days, giving values which would not have very greatly influenced results of continuous records. Special meteorological conditions may also have influenced the obtained figures. But, taking the uncertainty of the results into account, it is astonishing to see such a close agreement between the two curves. * * * Supposing that the fluctuations of the 'solar constant' and those of the monthly means of temperature observed at Arequipa coincide, which is far from being certain, as the diagram shows that a delay is more probable, I compared the Mount Wilson measurements with the Arequipa monthly departures of temperature. To have

* The Solar Constant and the Variations of Atmospheric Temperature at Arequipa and some other stations. Bulletin American Geographical Society, vol. 44, 1912, pp. 598–606.

comparable figures I made monthly means of the 121 observations taken at Mount Wilson from June to October 1905 and from May to October 1906. The differences between these figures, compared with the differences between the departures of the corresponding months, led me to the supposition that a departure in temperature of 1° F., in a monthly mean observed at Arequipa, is due to a departure of about 0.015 of the 'solar constant' from its normal value. If this is the case, we may admit that a comparably [comparatively?] small lowering of the 'solar constant,' if permanent, could produce climatical changes such as those which have really existed during the Pleistocene ice age. The required diminution would indeed fall entirely within the range of the momentary changes observed at Mount Wilson, the extreme values being 1.93 and 2.14 calories. But it is useless to make more far-reaching speculations, the acquired facts being sufficient to show the cause of the formation of pleions in tropical regions."

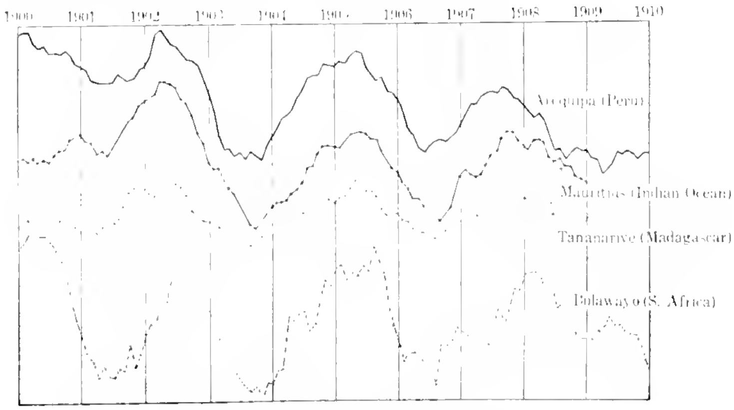


Fig. 82.—Monthly Departures of Temperature in South Equatorial Regions, showing Agreement, after Arctowski.

Arctowski's conclusion that the pleions of equatorial regions are really due to changes in the solar constant receives support from the fact that other places in the same zone of climate are characterized by similar variations. Thus figure 82 shows the smoothed curves of monthly departures for four stations having a latitude of from 16° to 20° S., but distributed well around the world in longitude. The agreement of the four curves is unmistakable. If seasonal variations played a part in the matter this agreement would possess no significance, but such is by no means the case. Each point on the curves represents the mean of 12 months, the middle point of a year representing the mean of one January to the following December, the next point February to the succeeding January, then March to February, and so forth.

The next diagram, figure 83, represents the similarly smoothed mean departures of four stations ranging across the torrid zone from Arequipa, latitude 16° 23′ S., through Batavia, 6° 10′ S., and Colombo, 6° 59′ N., to Bombay, 18° 54′ N. The upper three curves agree fairly well. Batavia, which has a typically equatorial climate of the simplest sort, has a curve like that of Arequipa except that it is less sinuous and the maxima of 1900 and the end of 1907 almost flatten out. Colombo in Ceylon has a climate similar to that of Batavia except that it is not quite so simple, being influenced somewhat by monsoon winds due to the great size of Asia. Its curve, however, resembles that of Batavia, except that it is decidedly more irregular and lags a little behind that of Arequipa. Bombay, the most northern of our stations, is quite different from the rest. Probably this is because its climate is highly complex by reason of the strong contrast between the northeast monsoons or trades of the dry winter and the southwest or true monsoons of the rainy summer. Its curve, then, as might be expected, shows the same periodicity as that of the other stations, but with a lag of a year or more in the main crests and with the curious addition of minor crests corresponding to the Arequipa crests, as occurs in the years 1905 and 1907. It is as if the departures from the mean temperature at Bombay were due to the same cause as those at Arequipa and the other stations, but the direct effects of this appear to produce only minor maxima, such as those of 1905 and 1907, while the greatest effects are produced after a delay of a year or so, during which the excess of temperature accumulated farther south is perhaps brought north by ocean currents driven by the monsoons.

The supposition of a delay of this sort is strengthened by the curves presented in figure 84. Here Arctowski has compared the departures from mean temperature at Arequipa with those of a series of stations from Key West along the Atlantic coast to Eastport. Here, just as in the other case, agreement gives place to disagreement when a pronounced disturbing factor is introduced. The curves for Key West, Tampa, and Savannah agree quite closely with that of Arequipa from 1900 to 1905, when the maxima come in winter, but thereafter they disagree markedly when the Arequipa maximum comes in summer. In this case the factor is not the monsoons, but may be the concentration of warm equatorial

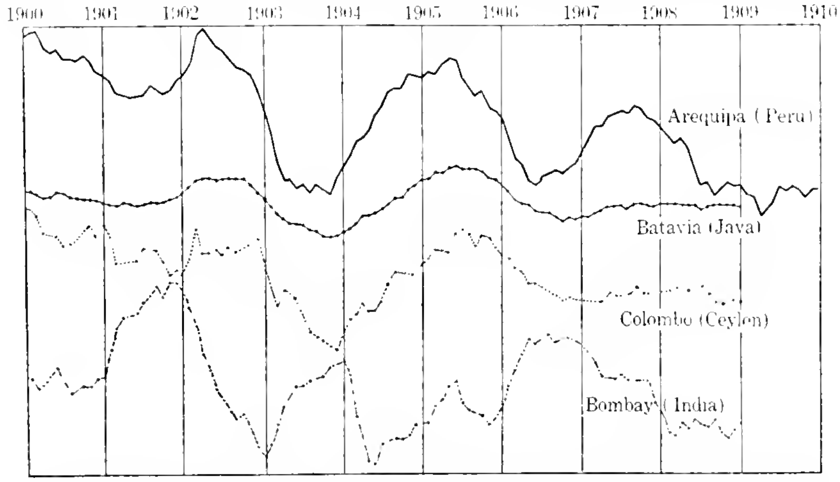


FIG. 83.—Monthly Departures of Temperature in North and South Equatorial Regions, Showing Disagreement, after Arctowski.

waters to form the Gulf Stream. North of the West Indies conditions once more change, and New York agrees with Arequipa, but with a delay of a few months. This may mean one of two things: either the temperature of New York responds directly to the same stimulus as Arequipa, perhaps because of its dependence upon a great continent easily warmed, or else (which seems much less likely) it responds indirectly and with a delay approximately equal to the average lapse of time from one Arequipa minimum to the next. This might happen if the variations of the New York temperature were largely dependent on the Gulf Stream, but as a matter of fact they depend more largely upon great interior regions whence come our westerly winds.

The sun's radiation is distributed equally to all parts of the earth, but the inclination of the axis, the variations of the seasons, the distribution of land and sea, the presence of clouds, the movements of winds and ocean currents, and a host of other accidental circumstances cause it to be concentrated now in one place and now in another. In equatorial regions and in the North Atlantic Ocean there is a permanent concentration, so that the temperature is relatively high. Over the continents a temporary concentration occurs in summer. If the sun's total gift of heat to the earth is thus irregularly distributed, the effect of any variations from the average must be distributed in the same irregular fashion, being concentrated at the equator or over the North Atlantic at all times, over the continents in summer, and in other places according to local circumstances. A result of this concentration is perhaps seen in the middle of 1901. At Arequipa (for some reason which we will temporarily assume to be the variation of solar radiation) a slight rise of temperature took place at this time; north of the equator this rise causes a hump in the curves for Key West, Tampa, and Savannah; at Raleigh it produces a distinct though unimportant maximum; at New York this maximum has become important, although not of the first rank, while still farther to the north and east it becomes a primary phenomenon.

In similar fashion other peculiarities can be traced throughout all the curves. Take the month of March 1906, for example. The Arequipa curve shows merely an insignificant little hump; in the Key West and Tampa curves this begins to become important: in those of Savannah, Raleigh, and Washington it becomes of primary importance, while farther to the northeast it once more drops into insignificance. Almost any of the other peculiar features of the curves can similarly be seen to show a maximum development in certain latitudes, and from there to decrease in intensity but by no means to disappear. If Arctowski's pleions are due to variations in the sun's radiation, we should expect exactly this—that is, we should expect to find that they would vary in intensity and in their place of origin, according to the season and other circumstances which determine where the sun's heat is most concentrated. Thus it may happen that at one time a wave of excessive temperature originates in the hot center of the United States during summer, let us say, and produces its maximum effect there only a short time after its origin, while under other circumstances the origin of the wave may be in the North Atlantic Ocean, or south of the equator, and its effect may reach the central United States only in an attenuated form after much delay.

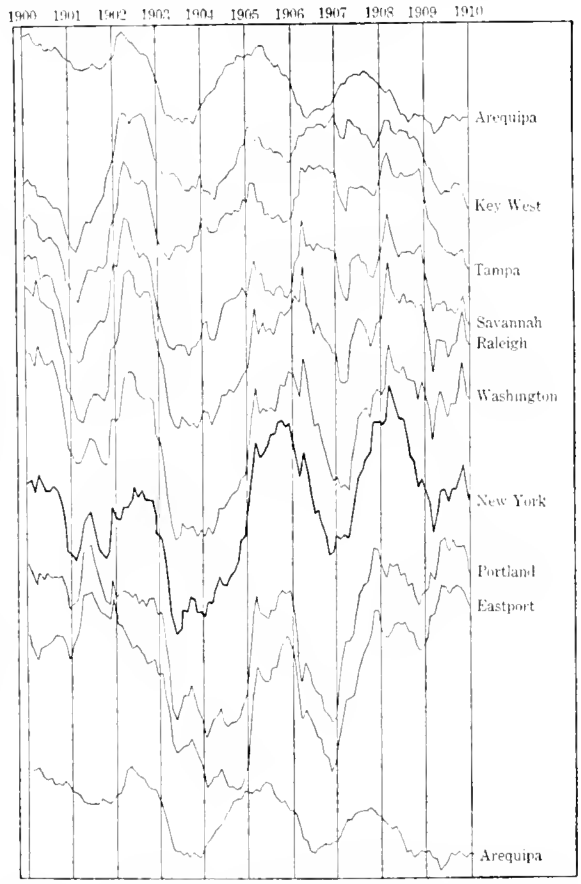


Fig. 84.—Monthly Departures of Temperature in North America Compared with Arequipa in Peru, after Arctowski.

The Arequipa curve is plotted on a vertical scale double that of the others.

Taken as a whole the work of Arctowski seems to indicate three things:

(1) In regions having a pure equatorial climate little influenced by outside causes, variations of terrestrial temperature show a general agreement with variations in the solar constant.

(2) Regions having a more complex climate, with temperatures dependent upon the movement of large bodies of air and water, show the same type of variations, but with pronounced irregularities and with a certain degree of delay; that these variations of temperature are the same as Arctowski's pleions and anti-pleions can scarcely be questioned; the pleions and anti-pleions of temperature appear to influence winds and storms, and thus to determine the amount of rainfall, but this result is not necessarily direct nor immediate, so that there is opportunity for the merging of one pleion with another or for the development of other irregularities.

(3) The response of vegetation (and especially of great trees like those of California) to the variations in rainfall involves still other delays and opportunities for the obliteration

of some maxima and the accentuation of others. Hence, if it be true that solar changes influence terrestrial climate, we should expect that in some places the results would be immediately and clearly visible, while elsewhere they would be masked in such a way as to be invisible when comparison is made between such phenomena as the sun-spot curve and the curve of growth of great trees like the sequoias; yet even here, if we examine long periods and obtain averages of many sun-spot cycles, we should expect to find some trace of the influence of the sun. And this is exactly what we find; the trees of Germany (which depend upon summer rains and have only a slight conservation factor) vary their rate of growth in close harmony with the sun-spot cycle. The sequoias of California, on the contrary, with their winter precipitation and large conservation factor, show in their growth the same general periodicity as the sun-spots, but individual maxima or minima by no means agree with those of the sun. Yet when the growth of a century or two is considered the trees are found on an average to grow relatively fast when the sun-spots are at a maximum, and slowly when they are at a minimum.

The work of Arctowski does not exhaust the recent contributions to our knowledge of ways in which the effect of solar radiation upon terrestrial climate may be modified. While the proof of this volume was being read there came to hand a paper by Abbott and Fowle,* two students of solar physics who have done much to demonstrate the existence of a relationship between solar radiation and terrestrial temperature. They now show that during the summer of 1912 volcanic dust from the volcano of Katmai in Alaska seems to have filled the upper air to such an extent that it decreased the amount of solar radiation received on the earth's surface by about 10 per cent of the normal solar constant. Moreover, they present a certain amount of evidence indicating that other volcanic eruptions, such as that of Krakatoa in 1883 and Bandai-San in Japan in 1888, have produced similar effects. The most important part of their paper, however, is a diagram which is not reproduced, but which in all essentials is almost identical with figure 85. This shows a previously published set of curves comprising the sun-spot curve from 1880 to 1909, the curve of departures from the mean temperature at 15 stations in the United States, and a similar curve of departures for the whole world. These three curves, to quote Abbott and Fowle, show "a considerable degree of correspondence—yet it is not hard to see that there is also much discordance." They are among the pieces of evidence referred to on a previous page which on the whole lead to the conviction that terrestrial temperature varies in accordance with fluctuations in the spots of the sun. Our authors now add to their previous diagram a curve showing recorded variations in the intensity of the sun's direct radiation as measured at the earth's surface and as modified by such terrestrial phenomena as the dust of volcanic eruptions. They then combine this curve with that of the sun-spots in such a way that the sun-spot curve still predominates, but is considerably modified. The correspondence between this modified curve and the temperature curves, particularly that of the United States, is, as they truly say, "most striking."

After the preceding paragraph was written and when the page-proof of this volume was being indexed, still another important article on the same subject came to hand.† In this Professor W. J. Humphreys follows a line of reasoning almost identical with that of Abbott and Fowle, and comes to the same conclusion, but carries it farther. In an unpublished manuscript, which he has kindly placed at my disposal, he applies his results to the climatic changes of geological times, and emphasizes the importance of changes in continental form, oceanic currents, and related phenomena in a way which differs little from that employed by Professor Schuchert and myself in the remaining portions of this volume. The main points of difference between his ideas and those here presented are that in the first place he regards variations in solar activity as of negligible importance

* Volcanoes and Climate, by C. G. Abbott and F. E. Fowle, Smithsonian Mis. Coll., 60, No. 29. Washington, 1913.
† W. J. Humphreys, "Volcanic Dust and Other Factors in the Production of Climatic Changes, and their Possible Relation to Ice Ages." Bulletin of the Mount Weather Observatory, vol. 6, part 1, August 20, 1913, pp. 1–26.

so far as our present knowledge is concerned, while in the second place he strongly emphasizes the importance of volcanic dust, a factor whose importance has not hitherto been appreciated. Humphreys's main conclusion may be summed up in his own words:

"Variations in the average temperature of the atmosphere depend jointly upon volcanic eruptions through the action of dust on radiation, * * * and upon sun-spot numbers, through, presumably, some intermediate action they have upon the atmosphere (Bulletin Mount Weather Observatory, vol. 6, p. 25). * * * It appears, from various considerations, that, with a constant or nearly constant output of solar energy, the earth itself possesses the inherent ability of profoundly modifying its own climates, whether only local or world-wide. Thus, as the laws of radiation indicate must be true, and as observations, at least back to 1750, the date of the earliest reliable records, show, the temperature of the lower atmosphere is distinctly influenced by the amount of volcanic dust in the upper atmosphere, in the sense that when this amount is great the average temperature at the surface of the earth is abnormally low, and when the dust is absent this temperature is comparatively high. Hence, as there appear to have been several periods of great volcanic activity in the past with intervening periods of quiescence, it is inferred that volcanic dust in the upper atmosphere was at least an important factor in some, if not all, of the great and universal climatic changes that have left their records in abandoned beaches and forsaken moraines."

The work of Abbott, Fowle, and Humphreys seems so convincing that we can scarcely doubt that the presence of volcanic dust, temporarily at least, is an important factor in determining climatic conditions. The degree of importance, however, is open to question. This can be tested by two methods, first by seeing how far present conditions of terrestrial temperature and climate actually vary in harmony with the amount of volcanic dust, and second by ascertaining to what extent volcanic activity and glacial periods have been coincident during geological times. The test according to the first method is easily made by studying figure 85, which is a reproduction of the last part of Humphreys's main diagram and is to all intents the same as the diagram of Abbott and Fowle. According to these diagrams, volcanic dust does not appear to be the main factor in determining climatic variations, although it seems to be an important contributing factor. In figure 85, the upper curve *P* represents variations in the intensity of solar radiation as measured by the pyrheliometer. The curve dips suddenly in 1884 just after the eruption of Krakatoa, in 1902–3 when Pelé, Santa Maria, and Colima were in eruption, and in 1912 when Katmai in Alaska belched out dust. Another dip occurs in 1890–91 and may perhaps be due to Bandai-San in Japan and Bogoslof in Alaska, but this is by no means clear. The second curve (*S*) is that of sun-spots, reversed in order to bring the maxima at low levels and the minima at high. The third curve represents a combination of *P* and *S*. The lowest curve is the average departure from mean temperature at 17 American stations and 13 in other parts of the world. It seems to be representative of the world as a whole. Manifestly the temperature curve is closely similar to the curve formed by combining the pyroheliometer and sun-spot curves and its relationship to that can scarcely be doubted. When the temperature curve is compared with *P* and *S* individually, however, one sees at once that it bears a somewhat pronounced resemblance to *S* but very little to *P*. The logical conclusion would therefore seem to be that variations in the sun are the main factor in modifying terrestrial temperature, but their effect may be much modified by the presence of volcanic dust in the atmosphere.

My own investigations seem to confirm this conclusion. Before the appearance of the articles by Abbott, Fowle, and Humphreys, I had tested the relation of tree growth and volcanic eruptions according to the method employed with sun-spots and the growth of trees as explained on pages 238 and 239. That is, taking all the known volcanic eruptions since 1755 A. D., I gave each one a weight of 1, 2, or 3, according to its severity, and then computed the intensity of volcanic activity at different portions of the sun-spot cycle. The results appear as curve *J* in figure 76 on page 240, but all mention of the matter was omitted from the text until the present time because of the doubt attaching to the whole subject. The curve, however, was allowed to remain. When the smoothed volcanic curve is compared with the smoothed curve of tree growth, *I'* in figure 76, a certain amount of resemblance is seen, but this breaks down at the right-hand end of the curves, and is by no means so pronounced as the similarity between the curves of tree growth and sun-spots. Hence it would seem that this method, as well as that of Abbott, Fowle, and Humphreys, leads to the conclusion that although volcanic dust may at certain times have an important influence upon terrestrial temperature, and thus upon other climatic elements, the effect of solar radiation is much more important. The second method of testing the control of climate by volcanic dust has been used by Professor Schuchert, in Part II of this volume. It is so purely geological that I shall leave it for the next chapter. Meanwhile, so far as present conditions are concerned, we seem to be led to the conclusion that although the solar hypothesis can not be regarded as proved, and although other factors, such as volcanic dust, have played an important part, changes of the sun seem, on the whole, to explain the known facts better than any other hypothesis yet suggested. Present changes in the intensity of the sun's radiation not only seem to be of sufficient amplitude to produce distinct climatic effects, but the time of their occurrence seems to be in harmony with the observed variations of climate. The reason this has not hitherto been realized seems to be partly that due allowance has not been made for the fact that the effects of the sun's heat are concentrated on certain portions of the earth's surface and can not reach other places and influence the other meteorological elements without the lapse of an appreciable and variable amount of time. An equally important or even stronger reason seems to be that the function of volcanic dust in modifying terrestrial temperature has only recently been discovered.

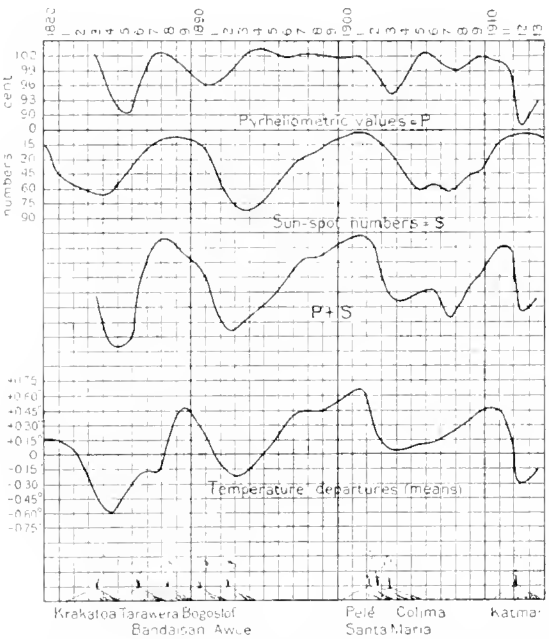


FIG. 85.—The Relation of Volcanoes, Sun-spots, and Terrestrial Temperature, after Humphreys.

Turning now from the minor climatic fluctuations of the present time to the fluctuations of all sizes from glacial epochs downward, let us sum up our conclusions:

It appears, in the first place, that of the well-established hypotheses of climatic changes only the solar and volcanic hypotheses invoke causes capable of varying and actually known to vary with sufficient rapidity to cause changes of climate such as the trees of California appear to give evidence of during the past three thousand years.

In the second place, numerous authorities, including the majority of meteorologists, believe in the existence of a climatic cycle related to the sun-spot cycle, and the trees of Germany and California, as well as the prices of wheat in England, add their quota of evidence to this same effect.

Thirdly, the sun's radiation is universally acknowledged as the controlling factor of terrestrial climate. It has been proved to vary from one extreme of the sun-spot cycle to another, but the amount of variation is held by so high an authority as Newcomb to be too slight to cause appreciable meteorological phenomena. Nevertheless, a comparison of his results with the conclusions of students of the glacial period suggests that the solar variation in the eleven-year cycle is quite sufficient to cause appreciable meteorological results, though the effect of either extreme is largely neutralized by a speedy change to the other.

Finally, the great objection to the solar hypothesis has been that while abundant indications of an eleven-year climatic cycle have been found, it has rarely been possible to point to specific terrestrial phenomena as the result of specific solar phenomena. The work of Arctowski, Abbott, Fowle, and Humphreys supplies this deficiency and suggests that the constantly varying conditions of the earth's surface may induce a given solar variation to produce its chief effect sometimes at one point and sometimes at another, or that the obstructive action of volcanic dust may shut out solar radiation for a time in certain areas or even in all parts of the world. Moreover, effects which appear to be due to solar variation seem to be transmitted in the form of waves or by means of winds and currents and thus may not reach a given point until after a delay of more or less duration. All things considered, the solar hypothesis seems to fit the facts better than any other, so far as the changes of climate indicated by our tree curves are concerned. The theories of precession, elevation, and carbon dioxide seem too slow and ponderous to account for changes which last only 1,000 years or less and are geologically very rapid and small. On the other hand, from the standpoint of man's history, a change whose duration is 1,000 years is relatively slow and important, and is probably too large to be due to purely terrestrial causes, such as accidental perturbations in the atmosphere. Volcanic activity, on the other hand, may vary either in long or short intervals, and thus meets all the requirements in this respect, but the actual curves which record its variations fail to show any marked agreement with the general course of climatic phenomena, although they show marked agreement at selected periods. The sun, however, seems to meet all the requirements. It is known to vary on a small scale, it is certainly adequate to produce the observed effects, and there is no reason why its variations should not in the past have been on a larger scale than at present. Whether the sun could vary sufficiently to produce all the climatic variations of geological times, and whether it was the only cause of those variations, is another question, which will be discussed in the next chapter.

NOTE.

The completion of the new work of Professor Kullmer mentioned on p. 205 furnishes strong confirmation of the conclusions reached in this chapter. In an address before the Association of American Geographers at Princeton, January 1, 1914, he has shown that in the belt of the northern United States and southern Canada where storms on the average are most numerous, the number of storms varies almost directly in harmony with the number of sun-spots, just as is the case with tropical hurricanes. In other areas, however, the reverse appears to be true, and there is a decrease in storminess. The general conclusion seems to be that when sun-spots are few in number cyclonic storms move in a great variety of tracks, but when spots are numerous the storms tend to confine themselves to a few well-defined tracks, so that storminess is more or less restricted to certain areas within which it is highly concentrated. Under such conditions it is possible for pronounced climatic changes to occur with only a minimum variation in the mean temperature of the earth as a whole.

Kullmer's work has led the present author radically to revise the conclusions set forth in this chapter. While the general conclusions are not changed they are greatly amplified, and thus lead to a wholly new form of the solar hypothesis, and to a new conception of such phenomena as the formation of loess during glacial periods, or the localization of glaciation during the Permian era. These new conclusions are fully set forth in a paper entitled "The Cyclonic Solar Hypothesis of Climatic Changes," which will probably appear in the Bulletin of the Geological Society of America during 1914.

CHAPTER XX.

CRUSTAL DEFORMATION AS THE CAUSE OF CLIMATIC CHANGES.

We have been led to the conclusion that among the four chief hypotheses of climatic change only the solar hypothesis seems competent to explain the pulsations, large and small, which have taken place from the glacial period to the present time. In the case of the greatest of all climatic changes, however, this theory in its turn appears to be inadequate. So far as we can see, no possible change in the sun's radiation, or in volcanic activity, could cause such a complete redistribution of the earth's climatic zones as we find in the Permian and other eras. It might cause the zones to be pushed greatly toward or away from the equator, to contract or expand, and to vary considerably in temperature, but it could scarcely cause them to be reversed in such a way as to make the polar regions as warm as the equator. The carbonic acid theory, in spite of ingenious attempts to indicate a possible method to the contrary, also seems to many geologists inadequate to produce any such result, and even the framers of the theory admit that this is the case. They fall back upon the well-established theory of changes in the form and altitude of the lands, and consequent alterations of oceanic and atmospheric circulation. Other students suggest that the peculiarities of Permian times may have been due to a shifting of the earth's axis of rotation, but astronomers and physicists find so many objections to this hypothesis that we can not wisely lay much stress on it.

Before discussing this matter any further and suggesting a possible relationship between solar changes and crustal deformation, it will be well to review the climatic history of geological times as a whole. In such a review there is much opportunity for the exercise of personal judgment. In this respect it is harder to deal with geological times than with the historic period wherein we can rely upon actual records, such as those of the growth of trees. In order to obtain as unbiased a statement of the facts as possible, I have asked Professor Charles Schuchert to contribute a discussion of geological climates. This discussion is probably the fullest and most authoritative that has yet appeared. It is printed as the concluding portion of this volume. Professor Schuchert wrote his paper without regard to the theories discussed in this book, and without definite knowledge of them. His statements may be taken as representing the mature conclusions of the most advanced students of geology and paleontology. Where matters are doubtful, he has clearly stated the doubt, but so far as our present problem is concerned the points wherein geologists disagree are not of vital importance. The student who would understand the matter thoroughly is referred to Professor Schuchert's paper. In the following paragraphs I shall recapitulate some of his chief conclusions, and shall see how they bear on those already reached in this volume.

The study of paleometeorology, as set forth by Professor Schuchert, leads to the conclusion that the earth has passed through a considerable number of great climatic changes, either glacial periods or other periods marked by a pronounced decrease in temperature or increase in aridity. The best-known is of course the Pleistocene glacial period. Equally important, though more remote and less well known in detail, is the glacial period of early Permic time. Both glaciations were world-wide in their effect, and were characterized by a change in temperature sufficient to occasion vast accumulations of snow and ice, not only in polar regions and at high altitudes, but even more markedly at low levels in middle or almost equatorial latitudes where the glaciation in many places reached the sea. The continental glaciers of Pleistocene time were located mainly in the northern portion of the northern hemisphere, while those of Permic time reached their greatest extent 20° to 40° south of the present equator, and to a less degree between 20° and 40° north of the equator. The Pleistocene glaciation was general in the arctic region, while that of Permic times almost certainly did not prevail in that region. Both periods of glaciation apparently consisted of a series of glacial and interglacial epochs, as is clearly brought out by Professor Schuchert. The evidence consists in part of an abundant interglacial flora which is found in many cases between distinctly glacial deposits during Pleistocene glacial times, and of coal beds which, in Australia, are interstratified with glacial till of Permic age. These two things are typical of a great body of evidence which indicates that glaciation did not last uninterruptedly throughout either period. The climate apparently fluctuated back and forth between conditions which promoted glaciation and those which caused the ice to retire.

A rapidly growing body of evidence indicates that, in addition to the well-known Pleistocene and Permic periods of glaciation, there were at least two and probably three other periods not merely of local but widespread glacial climates. All of these were geologically very ancient and were earlier than the Paleozoic era. The last of them was at or near the close of Proterozoic time; another was still earlier, although its position is somewhat doubtful; the third was at the very beginning of Proterozoic time and almost at the beginning of earth history as known to geologists. One at least of these periods appears to have

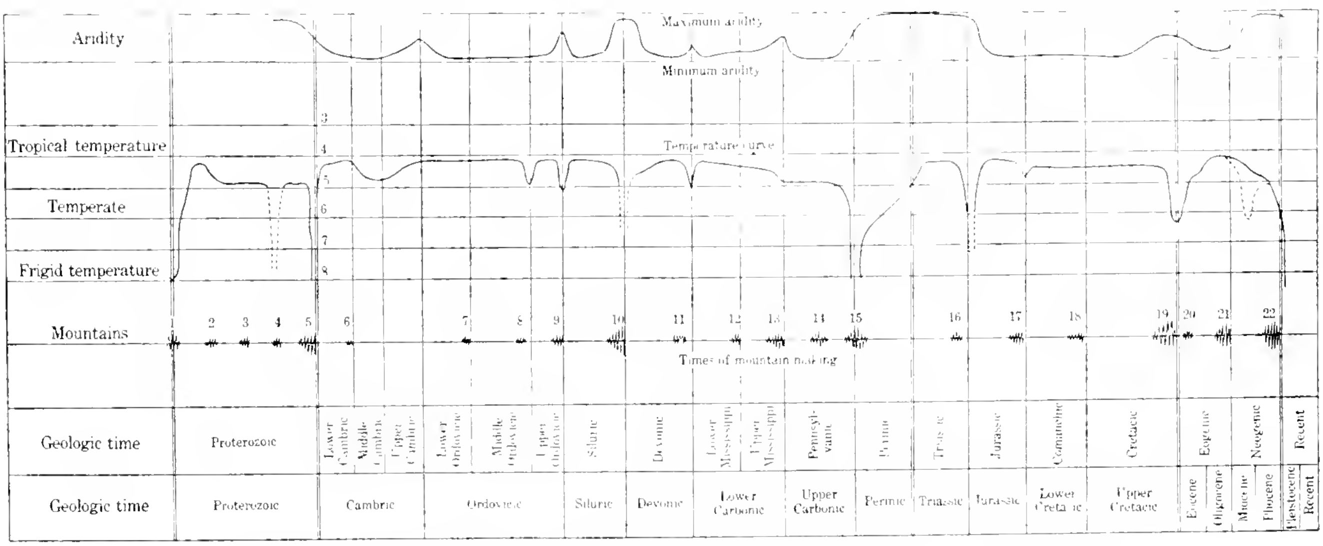


FIG. 86.—Geological Changes of Climate and Movements of the Earth's Crust. (After Schuchert.)

consisted of more than one epoch, for red deposits, apparently indicative of aridity or warmth, appear between glacial deposits. The number of glacial and interglacial epochs in this period may be considerable, although as yet our knowledge is incomplete. In the other two glacial periods of the Proterozoic era the evidence is as yet so slight that we can not tell whether they consisted of merely one epoch or of many.

Not even yet, however, as Professor Schuchert goes on to say, is the physical evidence of former glacial climates exhausted, for the notable Table Mountain tillites of South Africa point to a cold climate that occurred at least locally late in Siluric times. Finally, there may have been a seventh cool period in Liassic, that is, early Jurassic time, but the biologic knowledge so far at hand indicates that it was the least significant among the seven probably cool to cold climates so far discovered in the geological record. In addition to the seven periods when the climate was so cold as to cause glaciation or a close approach thereto, there have been various other periods of sudden cooling similar in character to glacial periods but less marked. All of these are indicated in the chart, figure 91, which accompanies Professor Schuchert's paper, and part of which is here reproduced in figure 86. The curves scarcely need explanation. The lower one indicates the probable course of variations of temperature during geological times. The high portions indicate a tropical climate and the low portions a frigid climate. It should be noted that the curve is the reverse of those used in the previous portions of this volume, in which high places, not low, indicate an approach toward the conditions which induce glaciation. The upper curve of figure 86 indicates the degree of aridity, the high portions indicating great dryness and the low portions relative humidity. It will be seen at a glance that in a large number of cases the evidences of great aridity and of glaciation appear at about the same time. This may perhaps indicate that glaciation and aridity are due to the same cause. It is equally possible, however, that the approximate coincidence of the two phenomena merely indicates that we have to deal with periods of great climatic instability, during which epochs of glaciation alternate with interglacial epochs of aridity. One of the Proterozoic glacial periods and also the Permic and Pleistocene periods, as we have seen, point to this conclusion, and the others neither support nor oppose it, for our knowledge of them is still so fragmentary that no conclusion is possible.

Turning now from the question of the succession of glacial periods, let us see what Professor Schuchert has to say as to their relation to movements of the earth's crust:

"Of the four more or less well-determined glacial periods at least three, earliest Proterozoic, Permic, and Pleistocene, occurred during or directly after times of intensive mountain-making, while the fourth, late Proterozoic, apparently also followed a period of elevation. * * * On the other hand, the very marked and world-wide mountain-making period * * * during late Mesozoic and earliest Eocene times was not accompanied by a glacial climate, but only by a cooled one. The cooled period of the Liassic also followed a mountain-making period, that of late Triassic times."

An inspection of Professor Schuchert's diagram, as reproduced in figure 86, shows that the agreement of mountain-making epochs and periods of climatic change is even closer than he has indicated. In his diagram Professor Schuchert shows 22 periods of mountain-making. Among these 22, Nos. 1, 4, 5, 10, and 15 accompany or immediately precede great changes of climate. Nos. 19, 20, and possibly 21 are associated with distinct, but less important changes, and No. 22 is associated with the great Pleistocene glacial period. Small changes of climate accompany or follow the mountain-making epochs Nos. 2, 6, 8, 9, 11, 13, and 17. The only mountain-making epochs not accompanied by a climatic change of some sort, as indicated by Professor Schuchert's lines of temperature and aridity, are Nos. 3, 7, 12, and 18—only 4 out of 22. It is possible that these mountain-making periods were also accompanied or followed by changes of climate, and that this does not appear simply because the changes, like the mountain-making, were of relatively slight magnitude and hence have escaped detection. This would scarcely be surprising, since it is only about 30 years since the possibility of Permian glaciation began to be seriously discussed, and practically all our knowledge of coolings of the earth's climate aside from the Pleistocene and Permian glaciations has been obtained during the present century. A basis of 18 out of 22 possible cases seems, then, to be good ground for Professor Schuchert's statement that "cooled and cold climates, as a rule, occur during or following periods of marked mountain-making." Yet the agreement between periods of mountain-making and of cool climates is by no means perfect; for, as Professor Schuchert indicates, the degree of cooling is not proportional to the intensity of mountain-making. This appears to be especially noticeable in late Mesozoic and early Eocene times, and to a less extent in upper Mississippian and late Oligocene. In all these cases the mountain-making is proportionally much more intense than the accompanying climatic change. Moreover, it must be remembered that when we speak of cool climates we do not mean that the climate became cooler merely among the uplifted mountains. Of course the fact that a given region was uplifted necessarily made it cooler than formerly, but the geological record preserves little evidence of this. The subaerial formations which have come down from those early times were almost wholly deposited at low altitudes, for otherwise they could not have been preserved. Many were manifestly laid down near sea-level, for they are interstratified with marine deposits. Moreover, a large part of the evidence as to the climate of ancient geological times comes from marine fossils. Accordingly, when we speak of periods of cool and cold climates, we refer to conditions at sea-level. It may be that pronounced crustal deformation would cause the earth's climate to become cool even at sea-level, because of changes in oceanic and atmospheric circulation. Possibly also the reduction of the amount of aqueous vapor in the air by reason of an increase in the size of the continents would add to this effect. Yet, according to the law of chances, mountain-making, and especially the upheaval of continents, ought often to cause vast oceanic areas to become warmer than hitherto instead of colder; for cold currents would be prevented from reaching low latitudes as often as they would be permitted to reach them, and warm currents would be similarly affected whenever barriers were interposed. Therefore we ought in many cases to find that periods of mountain-making and continental uplift are followed by periods of warmth over a considerable portion of the earth. This result might be less marked than a cooling effect, for any increase in the number of land barriers would tend to isolate certain polar portions of the ocean and to prevent them from being warmed by currents from the equator. Nevertheless we should scarcely expect to find so preponderating a tendency toward cool conditions, even in low latitudes, whenever pronounced movements of the earth's crust take place. Hence some other cause of climatic variation seems necessary. Moreover, such movements can scarcely account for the comparatively rapid succession of cold glacial and warm, or arid, interglacial epochs, a fact which Professor Schuchert takes care to indicate. Hence, from this point of view also, some other cause seems needed.

After discussing the relation of mountain-making and climate, Professor Schuchert takes up the new volcanic theory of climate and tests it by the geological record. He shows that although mountain-making and cool climates are usually associated, there appears to be no correspondingly close association between cool climates and volcanism. This is especially noticeable at the end of the Mesozoic and during the Eocene, when the greatest known volcanic activity of geological times does not appear to have produced any marked glaciation. Moreover, the Permic and Pleistocene glaciations seem not to have been coincident with periods of exceptional volcanic activity, but followed them at intervals which, although not of great length geologically, must have been measured in hundreds of thousands of years. This is quite inconsistent with the volcanic theory, for there is no reason to think that even the finest volcanic dust remains in the atmosphere more than a few years. Accordingly unless further study shall disclose unexpected evidence of widespread volcanic activity coincident with glaciation, it seems wise to accept Professor Schuchert's conclusion that: "Volcanic dust in the isothermal region of the earth does not appear to be a primary factor in bringing on glacial climates. On the other hand, it can not be denied that such periodically formed blankets against the sun's radiation may have assisted in cooling the climates during some of the periods when the continents were highly emergent."

This conclusion, based on the whole extent of geological time, is almost identical with that which we have previously reached from a study of the short period of thirty years since careful measurements of solar radiation were begun, soon after 1880.

One other theory receives attention at the hands of Professor Schuchert, and here again his conclusion, based on a vast lapse of time, agrees with that which we have already reached on the basis of the changes during the past two or three thousand years. He can not accept the carbonic-acid theory of glaciation, for two reasons: In the first place, glacial periods seem to come on quickly, whereas changes in the carbonic-acid content of the air must be very slow. In the second place, glacial epochs alternate with interglacial epochs in a way which demands that the amount of CO_2 shall have varied much more rapidly than seems possible. Finally, no glacial period seems to have followed the enormous locking up of carbonic acid in the vast limestone deposits of the Cretacic, while strong glaciation followed the much smaller locking up of CO_2 during the Miocene and Pliocene. Moreover, the conclusions set forth in earlier portions of this book add still another strong argument against the carbonic-acid theory, for they show that the climatic changes of historic times appear to be of too long duration to be explained on purely meteorological grounds and yet are far too rapid to be due to changes in the amount of CO_2 in the air. Having excluded the carbonic-acid theory on these grounds, Professor Schuchert's final conclusion is that changes in the form and size of the continents and seas, together with the uplifting of mountain ranges upon the land and the diversion of oceanic currents and winds from one area to another, and the subsequent changes in the amount of aqueous vapor contained in the air, have been the chief factors in producing the marked climatic variations which characterize the geological record. "Briefly then," as he puts it, "we may conclude that markedly varying climates of the past seem to be due primarily to periodic changes in the topographic form of the earth's surface, plus variations in the amount of heat stored by the oceans. The causation for the warmer interglacial climates is the most difficult of all to explain, and it is here that factors other than those mentioned may enter."

Let us now sum up the evidence as to the various climatic hypotheses. Professor Schuchert's conclusion, being based upon the well-verified agreement of two distinct types of related facts, is much more weighty than any conclusion based upon purely theoretical grounds, and there seems to be good reason to accept it as in large measure correct. Yet it lacks finality in several respects. In the first place, the theory of crustal deformation makes no attempt to explain the small climatic changes now in progress. Secondly, it can not explain such occurrences as the marked changes which culminated about the time of Christ, about 1000 A. D., and about 1350 A. D. Thirdly, it can not explain interglacial climates. And lastly, it does not explain why mountain-making and continental uplift are usually accompanied by cool climates even at sea-level, although the law of chances would indicate that part of the time the uplifting of the land should be as potent in causing parts of the sea to become warmer as in causing them to become cooler. The volcanic hypothesis appears to be a useful supplement to the hypothesis of crustal deformation, but it fails to account for many of the most striking phenomena, and would seem to occupy a position of only secondary importance. In the first place, the occurrence of pronounced volcanic activity during geologic times does not appear regularly to coincide with pronounced glaciation. In the second place, although volcanoes can be shown to have had a distinct effect upon terrestrial temperature in the period since measurements of the sun began to be made with accuracy, the effect is sporadic. It appears to be by no means so important as the effect which seems to be exerted by changes in the sun, if we may judge from the agreement of the sun-spot curve with the curve of the earth's temperature. Our third hypothesis, that of carbonic-acid gas, seems to be unsatisfactory because it can not account for the rapidity with which climatic changes take place, and because times of maximum glaciation do not regularly follow times when the maximum amount of CO_2 is withdrawn from the atmosphere. This does not mean that we reject the idea that carbonic acid is an important cause of climatic changes, but merely that it seems safer to assign to it a contributory rôle. Variations in the amount of carbonic-acid gas in the atmosphere from year to year, apart from human manipulation, probably occur, though this has never been demonstrated by actual observation.

Turning now to the solar hypothesis, we find that the only serious objection to it is that we do not possess any direct evidence that the intensity of solar radiations has varied greatly in past times. In the nature of the case, no such evidence can ever be forthcoming. We do know, however, that during the few decades since measurements have been possible, it has been proved beyond question that the intensity of solar radiation actually varies, although the amount of variation may be small. Moreover, historic records of sun-spots tell us that the sun's activity has varied in the past, and there are indications that at certain periods the number or size of the sun-spots was greater than recently. When we compare solar changes with variations in the earth's climate during the past few decades, we find that the two agree in many different ways. We also find that if allowance is made for the unequal distribution of the sun's insolation over the earth's surface and for the effect of volcanic dust in shutting out the sun's heat, many of the apparent disagreements between solar and terrestrial phenomena disappear. If we suppose that in the past the sun's variations were like those of the present, but on a larger scale, we find an explanation of climatic change which appears to satisfy all the requirements. We may suppose that at certain times the sun was stimulated to unusual activity, just as it is to-day when we have periods of unusually numerous sun-spots, but to a greater degree. This stimulation would cause an increase in all the phenomena associated with sun-spots. If the latest conclusions of Hale and others are correct, the sun-spots are violent perturbations of a cyclonic character, whereby material from the lower part of the sun's atmosphere is carried into the upper part. This process, according to an interesting suggestion made by Humphreys and quoted in Professor Schuchert's portion of this volume, might so increase the density of the solar atmosphere that an appreciable share of the sun's radiant energy would be prevented from escaping into space. This would produce the same effect as the presence of dust in the earth's atmosphere, and would cause the earth's climate to become cool. The degree of cooling upon the earth, and upon the other planets, where the same result would ensue, would depend upon the amount of material in the solar atmosphere. The sun itself might conceivably be hotter than before, and probably would be, although the effect upon outside bodies would be diminished. The material thrown into the solar atmosphere would presumably be in the most comminuted form, perhaps molecular, and part might even escape into space. The remainder, however, would gradually fall back toward its place of origin. Thus the solar atmosphere would become clearer, although the process would take a long time. As the atmosphere grew clearer, more and more of the sun's radiation would escape into space and the earth would become correspondingly warmer. If the sun were actually hotter than normal, the clearing of its atmosphere would give rise to an interglacial epoch characterized by unusual warmth or by aridity. This would last until renewed solar activity caused the ejection of more material and the solar atmosphere once more became dense, thus causing another glacial epoch. The processes here suggested, together with those discussed in the following paragraph, would cause cold climates to develop rapidly and pass away more slowly. This would correspond with the conclusions of geology, and would also agree with the changes of the last 3,000 years in California, where the curve of the sequoia usually rises more rapidly than it falls.

At this point we must consider what would be happening to the earth's crust at such a time of unusual activity in the sun. According to Professor Schuchert the time when the sun would be filling its atmosphere with ejected material, and thus preparing the way for a cool period upon the earth, would be likely to be a period of pronounced crustal deformation. In other words, a stimulation of the earth's interior appears to take place at the same time that our hypothetical stimulation of the sun takes place. The stimulation of the earth causes crustal deformation, the upheaval of continents and mountains, the formation of barriers between adjoining portions of the sea, and a general change in the oceanic and atmospheric circulation with a consequent readjustment of climate. It generally also causes volcanic activity which may be of the quiet type where vast deposits of liquid lava are formed, as happened in the Deccan, or of the violent, explosive type. If explosive eruptions occur, still further climatic changes may be induced. To this would be added the effect of the great elevation and extent of the land in causing rapid weathering and erosion. Under such circumstances much CO_2 is set free from the rocks, and may in time become so abundant as to appreciably raise the earth's temperature. Thus it appears that in our completed hypothesis solar changes stand first in importance. With them, however, and perhaps inseparable from them, occur changes in the earth's interior whereby crustal deformation is induced. This, in turn, is usually associated closely with volcanic eruptions, and rarely takes place without them. It also gives rise to the processes whereby the amount of CO_2 is increased. All four types of activity, solar, crustal, volcanic, and erosional, appear to have a direct effect upon terrestrial climate. An accurate weighing of their relative importance may perhaps do much to explain the earth's climatic history.

The conclusion just stated seems to carry with it the assumption that there is some relation between deformation of the earth's crust and periods of instability and variable radiation in the sun. Such an assumption leads at once to the inquiry whether any possible cause can be assigned for coincident or related activities of the two bodies. It is easy to speculate as to hypothetical changes in the relation of the solar system to the rest of the universe, as to possible magnetic variations, or as to the passage of the solar system through portions of space characterized by conditions different from those in which it now finds itself, but such speculation is fruitless. Another line of inquiry relates to the possible passage of our system through swarms of meteorites so large and numerous that their collisions with the various members of the solar system would produce appreciable effects, but here again we have not the slightest basis for theorizing. It is perhaps more probable that the gravitative or magnetic forces of the sun itself cause that body alternately to fall into periods of quiescence or activity. This activity may be communicated to the earth in some such way as that in which the magnetic changes of the sun are known to produce an immediate terrestrial effect. Other lines of thought might also be suggested, but even to mention them would scarcely be worth while. All that we can say is that, in spite of the absence of any assignable cause, there seems to be some ground for the hypothesis that throughout the course of geological history disturbances of the earth and of the sun have occurred at about the same time. According to our present hypothesis, disturbances of the earth seem to have caused deformation of the crust, accompanied oftentimes by volcanic outbursts, and causing a redistribution of climatic zones in accordance with the new outlines of continents and the new courses of winds and currents. Those of the sun, on the other hand, seem to have caused that body to throb with pulsations of various lengths whose greatest effects are seen in glacial and interglacial epochs, while the minor effects appear in little cycles like those whose average lengths now appear to be about 11 and 35 years. Because of the earth's small size or rigidity, its activity appears to have come to an end more quickly than that of the sun, as appears from the fact that in general the upheaval of continents and mountain systems has preceded the periods of most marked climatic instability.

Beyond this it would at present be useless to attempt to go. Our suggestion of a possible relation between the internal activities of the earth and the sun is merely one among several working hypotheses. It seems to be the logical conclusion of our study of terraces, lacustrine strands, ruins, the growth of trees, the rise and fall of civilizations, and the occurrence of glacial periods in geological times. Yet its truth or falsity has nothing to do with the verity of our hypotheses as to these other matters. It may prove wholly wrong, but that does not in the least affect them. In the same way some other hypotheses, such as our inferences as to the relation of pre-Columbian civilization to changes of climate, may also prove to be insufficiently grounded and may have to be much modified, but this does not affect the remaining conclusions of this volume. To a less degree the same is true of our hypotheses as to the exact mechanism by which the conditions of one climatic zone may be shifted into another.

All these hypotheses with their varying degrees of certainty are subsidiary to one main conclusion. They fall if it proves untrue, but if they prove untrue its position remains unchanged, for it does not depend upon them. That upon which it does depend is the convergence of a large number of lines of evidence upon the single point of whether the climate of the earth has changed appreciably during the past few thousand years since history began. All the evidence seems to unite in indicating that such a change has taken place, and that it has been of a pulsatory nature. This, then, is our main conclusion, the one point around which all else centers. Doubtless the details as to the time of changes, and especially as to their relation to one another in different parts of the world, will require modification, for we have been able to gather only a small part of the facts. This matters little, however, provided we are headed in the right direction. The only essential is that each new venture shall advance us one short step on that most wonderful of roads which leads to the knowledge of what some men call the law of the universe, and others, more deeply thinking, call the law of God.

PART II.

CLIMATES OF GEOLOGIC TIME.

By CHARLES SCHUCHERT
Professor of Paleontology in Yale University

CHAPTER XXI.

CLIMATES OF GEOLOGIC TIME.

By Charles Schuchert.

The ancient philosophers imagined that the earth arose out of darkness and chaos and that its present form and condition came about gradually through the creative acts of an omniscient and omnipotent God. Certain Greek philosophers tell us that the world had its origin in a primeval chaos; others that it arose out of water or an all-pervading primeval substance with inherent power of movement; that the energy of this primal matter determined heat and cold, and that the stars originated from fire and air. It was Empedocles (492–432 B. C.) who first told us that the interior of the earth was hot and composed of molten material, an opinion he formulated after seeing the volcanic activity of the Sicilian Mount Etna, in whose crater he is said to have met his fate.

The geology of to-day still teaches that the interior of the earth is very hot, but that the material of which it consists is as dense and rigid as steel, and that little of the interior high temperatures attains the earth's surface because of the low conductivity of the rocky and far less dense outer shell. The older geologists believed that this shell originally was thin, and that therefore much heat was radiated into space, this idea being a natural result of the Laplacian theory of earth origin. In other words, they held that the earth was once a very small star which, in the course of the eons, gradually cooled and formed a crust. Therefore it was postulated that, because the crust formerly must have been thin, life began in hot waters and the climates of the geologic past were hot, with dense atmospheres charged with far more carbonic acid and water vapor than they now hold. The present type of climate with zonal belts of decidedly varying temperature and polar ice-caps was thought to be of very recent origin, resultant from a much thickened rocky crust. All of these conceptions are now greatly modified by the planetesimal hypothesis of Professors Chamberlin and Moulton, which teaches of an earth accreting around a primordial cold nucleus through the infalling of small cold bodies, the planetesimals, all of this material being derived from a spiral nebular mass formed by the colliding of two large bodies. As the nuclear earth grew in dimensions, so also was increased the gravitative pressure, gradually developing central heat which spread to the surface and there broke out in a long period of volcanic activity.

Our knowledge of glacial climates had its origin in the Alps, the land of magnificent scenery and marvelous glaciers, through the work of Andreas Scheuzer, early in the eighteenth century. This was at first only a study of the interesting local glaciers, but out of it gradually came about, especially through the studies of De Saussure, Hugi, Venetz, Charpentier, Schimper, and Louis Agassiz, the application of conditions observed in the Alps to the very widely distributed foreign boulders known as erratics and the heterogeneous accumulations of sands, clays, and boulders called tills. The engineer Venetz in 1821 pointed out that the Alpine glaciers had once been of far greater size, and that glaciation had been on a scale of enormous magnitude in some former period. By degrees the older conception that the erratics and tills were of flood, river, or iceberg origin gave way to the theory of colder climates and glaciers of continental extent. It was shown that the reduced temperature was finally succeeded by greater warmth, and that in the wake of the melting glaciers the land was strewn with erratics, with thick accumulations of heterogeneous rocks deposited at the edge of ice-sheets and known as moraines, and with great fans of boulder-clays and sands, all of this being the diluvium or deluge material of the older philosophers and the drift or tills of modern students of earth science.

Throughout more than a century of study we have learned how glaciers do their work and what results are accomplished by their motion plus the action of temperature, air, and water. The present geographic distribution of the glaciers, together with that of the glacial deposits, shows us that during the Pleistocene or glacial period the temperature of the entire earth was lowered. We also know that this cold period was not a uniformly continuous one, but that during the Pleistocene there were no less than four intermediate warmer climates, so warm indeed that during one of them lions and hippopotamuses lived in western Europe along with primitive man. We may now be living in another interglacial warm period, though more probably we are just emerging from the Pleistocene ice age. Figure 87 gives the known distribution of Pleistocene glacial materials.

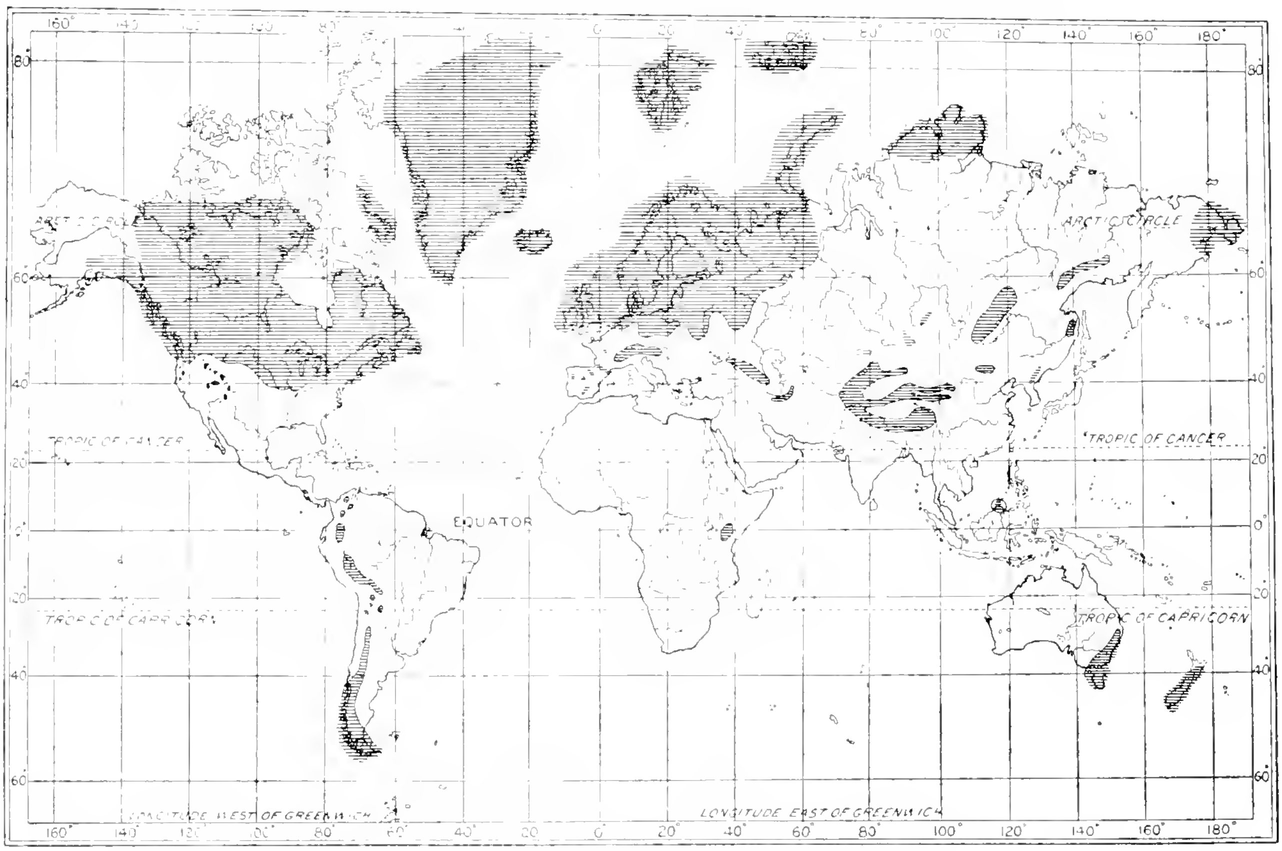


FIG. 87.—Map of Pleistocene Glaciation.

With the reduction of temperature, great variations also took place in the local supply of moisture, in the number of dark days, and in the air currents. How great these changes were in Pleistocene time is now being revealed to us through the work of the geologists, paleontologists, and ethnologists of Europe, where this record is far more detailed than in North America. These observations picture a fierce struggle on the part of the hardier organisms against the colder climates, a blotting out of those addicted to confirmed habits and to warmer conditions, and a driving southward of certain elements of the flora and fauna from the glaciated into the non-glaciated regions. The result was the disestablishment of the entire organic world of the Pleistocene lands, other than that of the tropics. More than once man and his organic surroundings have been forced to wander into new regions; the life of cool to cold climates has dispossessed that of milder temperatures, and with each moderation of the climate the hardier floras and faunas have advanced with the retreating glaciers, or become stranded and isolated in the mountains. As the organic world is dependent upon sunlight, temperature, and moisture, it is not difficult to see why these same factors are essential to man and his civilization.

PERMIC GLACIATION.

Hardly had the Pleistocene glacial climate been proven when geologists began to point out the possibility of earlier ones. An enthusiastic Scotch writer, Sir Andrew Ramsay, in 1855 described certain late Paleozoic conglomerates of middle England, which he said were of glacial origin, but his evidence, though never completely gainsaid, has not been generally accepted. In the following year, an Englishman, Dr. W. T. Blanford, said that

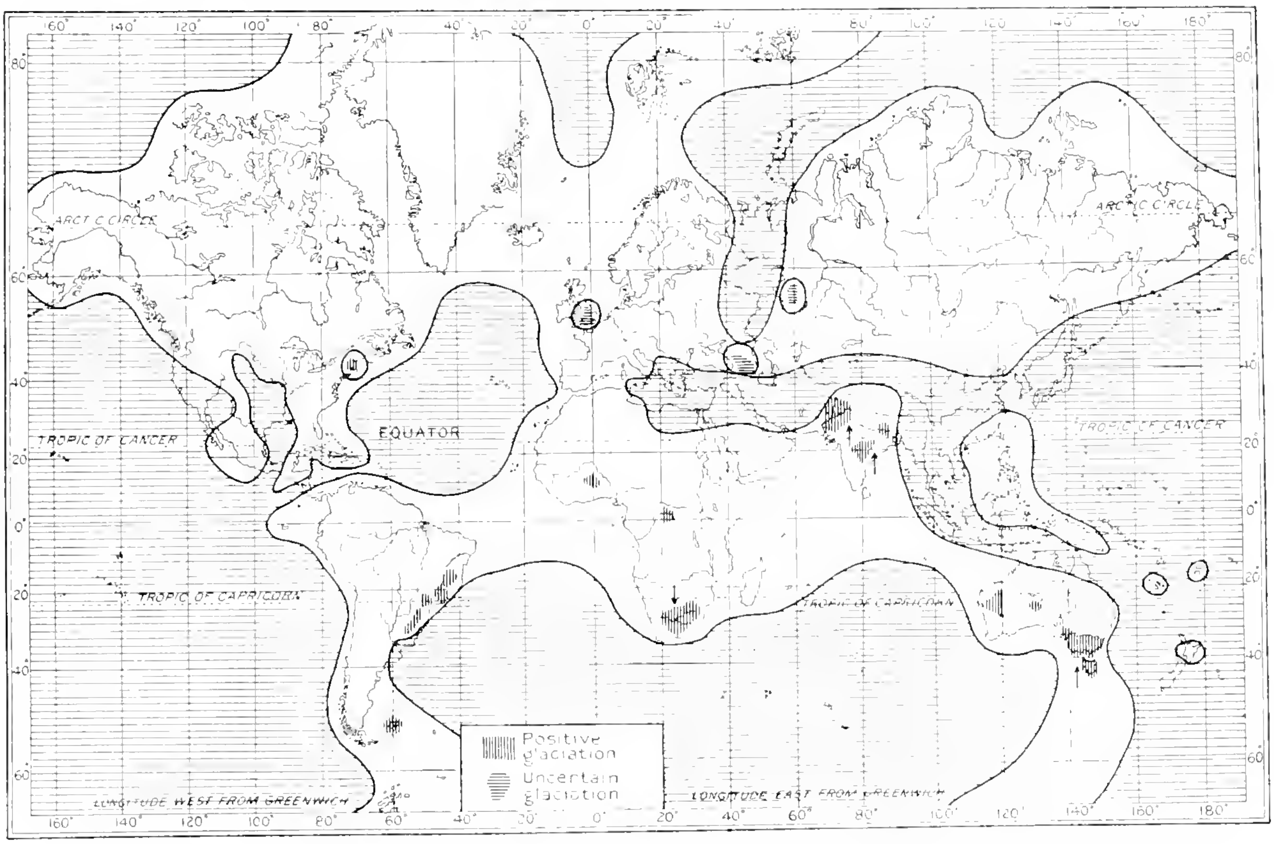


FIG. 88.—Paleogeography and Glaciation of Early Permic Times.

the Talchir conglomerates occurring in central and southern India were of glacial origin, and since then the evidence for a Permic glacial period has been steadily accumulating. The land of ancient tills (tillites of geologists) is Africa, and here in 1870 Sutherland pointed out that the conglomerates of the Karoo formation were of glacial origin, and, further, that they rest on a land surface which has been grooved, scratched, and polished by the movement of glaciers. Australia also has Permic glacial deposits. It is only very recently that the evidence found in many places in the southern hemisphere has become widely known, but so convincing is this testimony that all geologists are now ready to accept the conclusion that a glacial climate was as widespread in Permic time as was that of the

Pleistocene. This time of organic stress, curiously, did not affect the polar lands, but rather those regions bordering the equatorial zone, while the temperate and arctic zones of the northern hemisphere were not glaciated, but seem to have had winters alternating with summers. The lands that were more or less covered with snow and ice lay on each side of the equator—that is, roughly, from 20° to 40° north and south of this line, as may be seen in figure 88.

Geologists now accept the geographical occurrence of tillite deposits formed in early Permic time as follows: Throughout South Africa (widely distributed and with much fossil evidence, thickness of tillites up to 1,130 feet); Tasmania; western, southern, eastern, and central Australia (tillites up to 1,300 feet thick, both land and marine fossils); peninsular and northwestern India; southeastern Brazil (of wide distribution, with land floras and some marine invertebrates); northern Argentina; and the Falkland Islands. "It may be added that the plant beds of the Gondwana associated with the glacial deposits found near Herat [Afghanistan] are much like beds found in Russian Turkestan and Elburz, in Armenia, suggesting a still farther extension to the west [of India], and that a probably glacial conglomerate is known from the Urals" (Coleman, 1908A: 350). Heritsch records the presence of tillites in the Alps and Frech points out that a scratched surface occurs in the Ruhr coal field of Germany, on which the Rothliegende rests (Frech, 1908: 74). The Roxbury conglomerate with a thickness of 500 to 600 feet occurs in the vicinity of Boston and is interpreted as a tillite (Sayles and La Forge: 723–4). Then, too, the Lower Permic (Buntsandstein) of western Europe is now thought to indicate not only an arid but probably also a cool climate.

The greater part of these glacial deposits is ground moraines or morainic material carried by the land ice into the sea. Their wide distribution in the southern hemisphere clearly indicates that glaciation there was as effective in earliest Permic time as was that of the Pleistocene of the northern hemisphere. This Permic glaciation caused the development in the southern hemisphere of a peculiar hardy flora—the Glossopteris flora—of which very little is known in the northern hemisphere. Of this cold-climate flora the invaders and advance migrants arrived in Asia and Europe not before Middle Permic time.

In Africa and India the glacial condition appears to have been continuous during early Permic time, and there is as yet no convincing evidence here for interglacial warmer climates such as occurred in the Pleistocene. In Brazil, however, the evidence appears to indicate one warmer between two colder periods, and in New South Wales there is evidence of a series of recurrent colder and warmer climates. This condition is stated by Chamberlin and Salisbury as follows:

"In South Australia, above a series of Coal Measures, the plants of which are of the normal Carboniferous types, there is a series of marine beds alternating with beds which contain land plants unlike those of the Coal Measures below. Considerable beds of coal are also included in the series. Interstratified with these marine strata and coal seams there are considerable beds of conglomerate of distinctive glacial type. Some of the bowlders of the conglomerate are striated in such a way as to leave no doubt as to their glacier origin. Furthermore, the substratum on which the bowlder beds rest has been repeatedly observed to be grooved and polished, like *roches moutonnées.* * * *

"The number of well-defined bowlder beds is in places (Bacchus Marsh District, Victoria) not less than nine or ten, and some of them have a thickness of fully 200 feet. The marine beds with which they are intercalated have an aggregate thickness of 2,000 feet or more, and 30 to 40 feet of coal are included between the highest and lowest of the bowlder beds. The recurrence of the bowlder beds points to the repeated recurrence of glacial conditions, and the great thickness both of clastic beds and of the included coal point to the great duration of the period through which the several glacial epochs were distributed" (632).

In Africa, in the southern Dwyka region, there is also some evidence for interglacial warmer periods (Coleman, 1908A: 360).

DEVONIC GLACIATION.

In South Africa there occurs, beneath Lower Devonic marine strata, the 5,000-feet-thick Table Mountain series, essentially of quartzites with zones of shales or slates, which has striated pebbles up to 15 inches long, found in pockets and seemingly of glacial origin. There are here no typical tillites and no striated undergrounds have so far been discovered. While the evidence of the deposits appears to favor the conclusion that the Table Mountain strata were laid down in cold waters with floating ice derived from glaciers, it is as yet impossible to assign to these sediments a definite geologic age. They are certainly not younger than the Lower Devonic, but it has not yet been established to what period of the early Paleozoic they belong.

Elsewhere than in South Africa, late Siluric or early Devonic tillites are unknown. It is desirable here, however, to direct attention to the supposed tillites mentioned by Ramsay and found in the north of England in the Upper Old Red Sandstone of late Devonic time. Geikie (1903: 1001, 1011) states that this "subangular conglomerate or breccia recalls some glacial deposits of modern time." Jukes-Brown in his book, "The Building of the British Isles," 1911, writes of arid Devonic climates, but does not mention tillites nor glacial climates. Further details as to this and other pre-Permic glaciations are given in the Supplementary Notes at the end of this chapter (pp. 290–296), chiefly in the form of quotations from original sources.

CAMBRIC GLACIATION.

Unmistakable tillites, thought to be of earliest Cambric age, have been described by Howchin and David from southern Australia and by Willis and Blackwelder from China. In both cases the evidence as to age is open to question, as the tillites are either sharply separated from the overlying Cambric deposits or these strata have no fossils to fix their age, thus leading to the inference that the tillites are more probably of late Proterozoic time. In Arctic Norway occur other tillites at the base of the thick Gaisa formation. These deposits also were formerly regarded as of Paleozoic age, but Norwegian geologists now refer them to the Proterozoic. All of these tillites are best referred to the vast era previous to the Cambric period.

LATEST PROTEROZOIC GLACIATION.

Australia.—In southern Australia, conformably beneath marine and fossiliferous Lower Cambric strata but sharply separated from them, occur tillites of wide distribution. They extend from 20 miles south of Adelaide to 440 miles north of the same city, with an east-and-west spread of 200 miles. Boulder-clay has also been discovered on the west coast of Tasmania. The tillites range in thickness from about 600 to 1,500 feet and occur at the top of a vast pile of conglomerates, grits, feldspathic quartzites, slates, and phyllites, whose exact age is unknown because as yet no fossils have been discovered in them. (See figure 89.)

According to Howchin, the tillite consists "mainly of a ground-mass of unstratified, indurated mudstone, more or less gritty, and carrying angular, subangular, and rounded boulders (up to 11 feet in diameter), which are distributed confusedly through the mass. It is, in every respect, a characteristic till" (1908: 239). The first scratched boulders were observed in 1901 and now they are known by the "thousands" (David). They range in size up to about 10 feet long. So far, no striated underground or glaciated floor has been discovered, and both Howchin and David hold that the tillite was formed at or near sea-level in fresh or brackish water with floating icebergs. The rocks of the tills, David thinks, came from the south. The tillite is now found from below sea-level to about 1,000 feet above the sea. These tillites and all of the enormous mass of coarse deposits below them, which is at least several miles thick, the Australian geologists regard as of Lower Cambric age, because overlying them occur fossils of this time. The contact between the tillite and the marine Cambric is always a sharp one, leading to the inference that the sea of this time transgressed over an old flat land. Under these circumstances, deposition was not continuous, for the geologic section is here broken between the tillite and the Cambric deposits, indicating that the age of the former is rather late Proterozoic than early Paleozoic. From the evidence of the Lower Cambric life, to be presented later, we shall see that the waters of this time, the world over, were of tropical or subtropical temperature, conditions not at all in harmony with the supposed glacial climates of earliest Cambric time. (For further detail see pp. 291–93.)

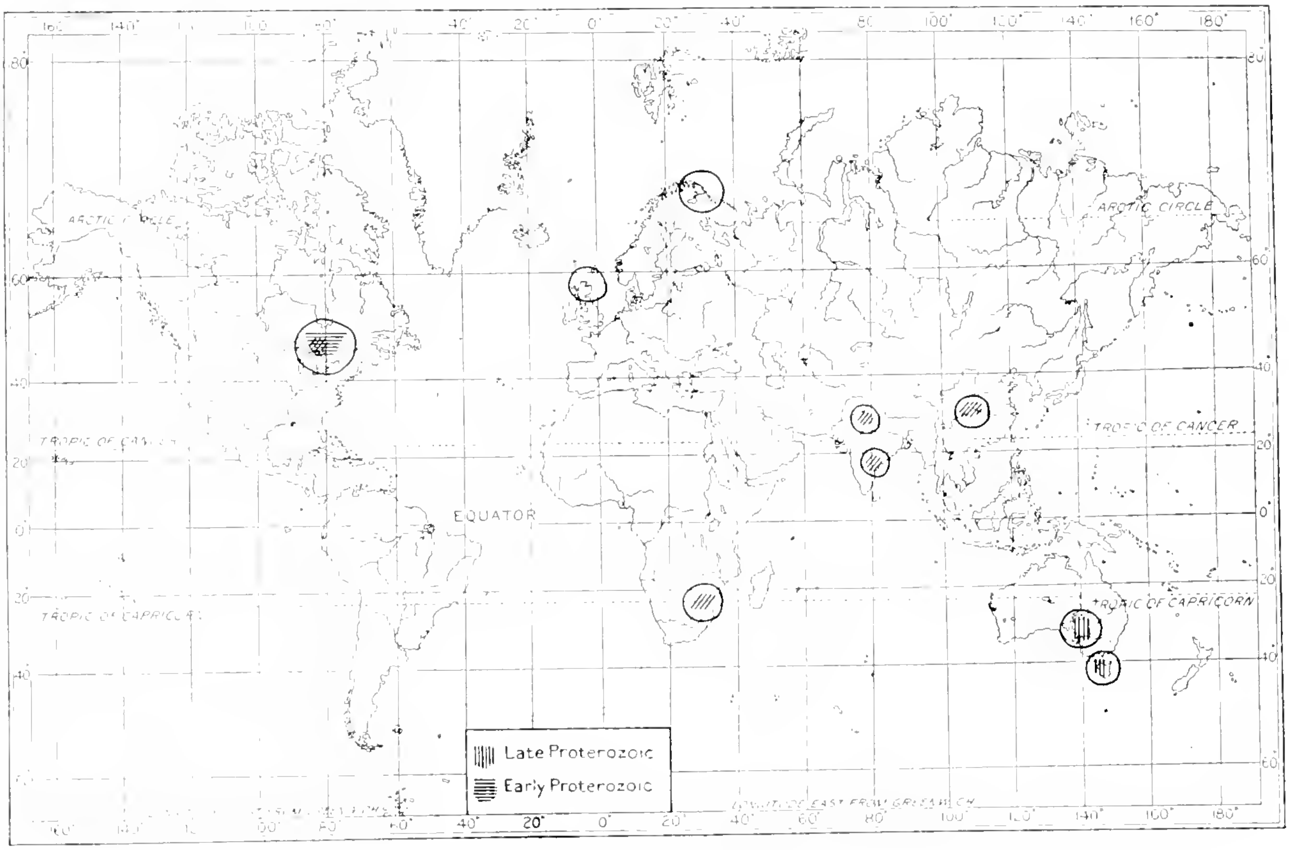


Fig. 89.—Map of Proterozoic Glaciation.

The Norwegian occurrence shown by an empty circle on this map is supposed to be late Proterozoic, but there is doubt as to the exact date. The occurrence in Great Britain and also the occurrences indicated by diagonal lines are undated Proterozoic.

Arctic Norway.—As long ago as 1891, Doctor Reusch described unmistakable tillites in the Gaisa formation in latitude 70° N. along the Varanger Fiord of Arctic Norway. Similar deposits are also known farther east on Kildin Island, and on Kanin Peninsula at Paë (Ramsay, 1910). At first the age of these deposits was thought to be late Paleozoic and even Triassic, but the Swedish geologists now correlate the Gaisa with the Sparagmite formation, one of the members of the Seve series. As the latter is overlain by the Lower Cambric fauna it appears best to refer the Gaisa formation to the top of the Proterozoic series. The tillite occurs at the very base of the Gaisa formation and overlies the ancient and eroded granites. Strahan reinvestigated the area originally studied by Reusch and his description of the geologic phenomena must convince anyone, not only that here are intercalated thin zones of sandstone and tillite in a series of red shales (these may indicate warmer and arid interglacial climates), but as well that the tillite rests upon a striated sandstone, the very ground over which the glacier moved. Strahan further states that "the Gaisa Beds, so far as I saw them, do not suggest the immediate neighbourhood of a mountain-region, for such conglomerates as they contain are neither coarse nor plentiful" (1897: 145). Again we have the evidence of tillites formed on low grounds and not in the mountains. (For further detail see pp. 292–3.)

UNDATED PROTEROZOIC GLACIATION.

The following occurrences of tillites do not appear to be of latest Proterozoic time, as do those of Australia and Norway. They are therefore held apart under a separate heading from the tillites of earliest and latest Proterozoic time.

North America.—Professor Coleman states that "Doctor Bell reports boulders reaching diameters of 3 feet 8 inches, having grooves like glacial striæ, in a conglomerate with sandy matrix belonging to the Keweenawan of Pointe aux Mines, near the southeast end of Lake Superior. Messrs. Lane and Seaman* describe a Lower Keweenawan conglomerate as containing 'a wide variety of pebbles and large boulders, in structure at times suggestive of till,' from the south shore of Lake Superior" (1908A: 354).

India.—In peninsular India occurs the Kadapah system, which, according to Vredenburg, is made up of several series separated from one another by unconformities. The Lower Kadapah is of Proterozoic age and the Upper Kadapah is certainly older than the Siluric and probably even than the Cambric. In the Upper Kadapah occur "remarkable conglomerates or rather boulder-beds consisting of pebbles of various sizes, some of them very large, scattered through a fine-grained slaty or shaly matrix. * * * These peculiar boulder-beds are regarded as glacial in origin" (1907: 20).

In Simla occurs the Blaini formation, also with boulder-beds, the age of which, according to Holland (see in David: 447) is certainly older than the Permic and possibly of late Proterozoic time. It is "a conglomeratic slate composed of rounded pebbles of quartz, ranging up to the size of a hen's egg, or in other cases angular and subangular fragments of slate and quartzite, of all sizes up to some feet across, which are scattered at intervals through a fine-grained matrix" (447). Holland regards these beds as "almost certainly of glacial origin" (448). They may eventually be shown to be of late Proterozoic age.

Africa.—In Proterozoic strata, far beneath the Table Mountain series of probably late Siluric or early Devonic age, is the Griquatown or Pretoria series (29° S. lat.), in which glacial materials have been found. At present no definite age in the Proterozoic era can be assigned this formation, nor can it be said that the glacial horizon is either that of the Lower Huronian or of the latest Proterozoic time. These are described by Schwarz as follows:

> "The Griquatown beds are a highly ferruginous series of shales and slates. * * * Near the top of the series, in the district of Hay, west of Kimberly, there is a well-developed glacial till, the matrix now converted into a red jasper; yet the bowlders of chert, when weathered out, show the unmistakable facetting and scratching which can have been caused only by glacial action. * * * The size of the bowlders varies up to 2 feet, and they are scattered at random through the matrix, to which they bear a very small proportion in regard to bulk. * * * I have found them in large numbers in some of the Witwatersrand conglomerates. The whole thickness of the glacial till is probably under 100 feet, but the extent of country covered by it in the area already mapped is over 1,000 square miles" (1906: 686).

China.—In the provinces of the middle Yangtse River of China (110° E. long. and 31° N. lat.) Willis and Blackwelder (1907: 264–9; 1909: 39–40) found resting unconformably upon very ancient granite and gneiss a series of quartzites followed by at least 120 feet of an unmistakable glacial tillite (in places nearly 500 feet thick), green in color, which is in turn overlain by unfossiliferous limestones over 4,000 feet thick. This limestone Willis correlates with the fossiliferous Middle Cambric occurring 100 miles away,

* A. C. Lane and A. E. Seaman, Jour. Geol., 15, 1907: 688.

and the tillite beneath it is thought to have formed "close to sea-level." The age of these tillites is conceded to be at least as old as the Lower Cambric, but when we note that the tillite changes quickly into the overlying limestone within a few feet of thickness, indicating a probable break in sedimentation between the two series of deposits, and the further fact that the overlying limestones have yielded no fossils, we see that these glacial deposits are as yet unplaced in the geologic column. Professor Iddings restudied these tillites in 1909, and he likewise could find no fossils in the limestone. For the present the tillites are referred to the Proterozoic. What their distribution has been in China is as yet unknown. (For further detail by Willis, Blackwelder, and Iddings, see pp. 293–5.)

Scotland.—In the northwest of Scotland are seen some of the oldest rocks known to the geologists of Europe. The basement formations make up the Lewisian series, comparable to the Laurentian of American geologists. Upon these old gneisses and schists, mainly of igneous origin, reposes unconformably a great pile of dull red sandstones, shales, and conglomerates, referred to as the Torridonian, that Peach states were laid down "under desert or continental conditions" (1912: 50). These attain a thickness of at least 8,000 to 14,000 feet, and are in turn overlain unconformably by Lower Cambric strata having the trilobite Olenellus and related genera. The Torridonian was laid down in part upon a mountainous topography of Lewisian domes strikingly suggestive of glacial erosion.

In western Sutherland and Ross, Geikie states that the observant traveler must be struck by the "extraordinary contour presented by the gneiss. A very slight examination shows that every dome and boss of rock is ice-worn. The smoothed, polished, and striated surface left by the ice of the glacial period is everywhere to be recognized. Each hummock of gneiss is a more or less perfect *roche moutonnée*. Perched blocks are strewn over the ground by thousands. In short, there can hardly be anywhere else in Britain a more thoroughly typical piece of glaciation" (1880: 401–3).

Over this eroded and smoothed ground was formed a coarse reddish breccia with many of the stones decidedly angular and "sometimes stuck on end in the mass." Some blocks are "fully 5 feet long" but none were found to be scratched or striated. The breccia "is quite comparable to moraine-stuff." The material came from a land that lay to the northwest and that has since sunk into the Atlantic.

Geikie as late as 1903 still stands by these conclusions, for he says:

"Sometimes, indeed, where the component blocks of the basal Torridonian conglomerates are large and angular, as at Gairlock, they remind the observer of the stones in a moraine or in boulder-clay" (1903: 891).

"Some of these *roches moutonnées* in N. W. Scotland may be of Palæozoic age [now classed as Proterozoic] and the Torridonian breccias which cover them have a singularly 'glacial' aspect" (1309).

"The resemblance of these rocks [Sparagmite] to the Torridonian series of Scotland is remarkably close" (899).

EARLIEST PROTEROZOIC GLACIATION.

Canada.—The oldest known tillite was recently described by Professor Coleman (see figure 89). It occurs at the base of the Lower Huronian in the so-called "slate conglomerate," and therefore near the base of the geologic column accessible to geologists. These conglomerates are found "from point to point across all northern Ontario, a distance of nearly 800 miles [now placed at 1,000 miles] and from the north shore of Lake Huron in latitude 46° to Lake Nipigon in latitude 50° [now placed at 750 miles]." "The appearance of these so-called slate or graywacke conglomerates is closely like that of the Dwyka bowlder clays of Africa" (1907: 189). They rest on various formations older than the Huronian, an "undulating surface of low hills and valleys, the conglomerate often more or less filling in these valleys" (191). A scratched or polished underground has been found in three places, but as a rule such are not seen because of the unfavorable conditions for their display. The evidence of the tillites is in favor of the view that glaciation in Huronian Canada was not "the work of merely local mountain glaciers," but rather due to "the presence of ice sheets comparable to those which formed the Dwyka. * * * This implies that the climates of the earlier parts of the world's history were no warmer than those of later times, and that in Lower Huronian times the earth's interior heat was not sufficient to prevent the formation of a great ice-sheet in latitude 46°" (192). (For further detail see pp. 295–6.)

CLIMATIC EVIDENCE OF THE SEDIMENTS.

During the past ten years it has become evident that the color of the delta deposits of geologic time, and especially that of continental deposits, is to be connected largely with differences in climate. This evidence, however, is as yet difficult of interpretation, because the climatic factors are not easily separated from those due to topographic form. All that can be done now is to call attention to the marked changes in sedimentation from the gray, green, blue, and black colors to the red beds which are so often also associated with coarser materials. Barrell states:

"The changes from the red beds of the Catskill formation, several thousand feet in thickness, to the gray Pocono sandstones with a maximum thickness of 1,200 to 1,300 feet, then to the sharply contrasted red shales and sandstones of the Mauch Chunk, 3,000 feet in maximum thickness, and back to the massive white conglomerates of the Pottsville conglomerate, 1,200 feet in maximum thickness, followed by the coal measures, are all the result of increasingly wide swings of the climatic pendulum which carried the world from Upper Devonian warmth and semi-aridity to Upper Carboniferous coolness, humidity, and glaciation" (1908: 163).

In regard to the significance of gray to black formations Barrell states:

"Where a whole formation, representing an ancient floodplain or delta, shows in its unweathered portions an absence throughout of the colors due to iron oxide, and a variable presence of carbon, giving grays to black, the inference is that the formation accumulated under a continuously rainy climate or one which in the drier season was sufficiently cool or cold to prevent noteworthy evaporation; such climates as exist in Ireland, Iceland, or western Alaska" (294).

On the other hand, the red colors in stratified rocks are in general due to arid and warm conditions.

"Turning to the climatic significance of red, it would therefore appear both from theoretical considerations and geological observations that the chief condition for the formation of red shales and sandstones is merely the alternation of seasons of warmth and dryness with seasons of flood, by means of which hydration, but especially oxidation of the ferruginous material in the floodplain deposits is accomplished. * * * The annual wetting, drying, and oxidation not only decompose the original iron minerals, but completely remove all traces of carbon. If this conclusion be correct, red shales or sandstones, as distinct from red mud and sand, may originate under intermittently rainy, subarid, or arid climates without any close relation to temperature and typically as fluvial and pluvial deposits upon the land, though to a limited extent as fluviatile sediments coming to rest upon the bottom of the shallow sea. The origin of such sediment is most favored by climates which are hot and alternately wet and dry as opposed to climates which are either constantly cool or constantly wet or constantly dry" (292–3).

Red sandstones and sandy shales recur at many horizons in the American Paleozoic strata and markedly so at the close of the Ordovicic, Siluric, Devonic, Lower and Upper Carbonic, and early Permic. The eastern Triassic beds, and those of the Rocky Mountains, are nearly everywhere red throughout, and there is considerable red color in the Lower Cretacic (Morrison and Kootenay) of the Great Plains area. Then, too, there are many red beds in the Proterozoic of America as well as of Europe. Between these zones of brilliant strata are the far more widely distributed ones of grays and darker colors, and these are the deposits of the times when the oceans have most widely transgressed the lands, and therefore the times of greater humidity. The maximum of continental extension falls in with red deposits and more or less arid climates. (See curve for aridity in figure 90.)

VOLCANIC DUST AS A CLIMATIC FACTOR.

As these pages are going through the press two interesting papers on the subject of volcanic dust as a climatic factor have appeared. These articles, which are by W. J. Humphreys,* should be read by every student of paleometeorology. The following are the conclusions reached:

[Volcanic dust in the upper atmosphere has been one of] "several contributing causes of climatic change, * * * a cause that during historic times has often been fitfully operative, and concerning which we have much definite information. * * *

"At an elevation that in middle latitudes averages about 11 kilometers the temperature of the atmosphere becomes substantially constant, or, in general, ceases appreciably to decrease with increase of elevation, this is, therefore, the upper limit of distinct vertical convection and of cloud formation. Hence, while volcanic or other dust in the lower or cloud region of the atmosphere is quickly washed out by snow or rain, that which by any process happens to get into the upper or isothermal region must continue to drift there until gravity can bring it down to the level of passing storms. In other words, while the lower atmosphere is quickly cleared of any given supply of dust, the isothermal region retains such dust as it may have for a time that depends upon the size and density of the individual dust particles themselves, or upon the rate of fall. * * * Volcanic dust once in the upper atmosphere must remain in it for many months and be drifted out, from whatever origin, into a thin veil covering perhaps the entire earth. * * * A veil of volcanic dust must produce an inverse green-house effect, and if long continued, should perceptibly lower our average temperature. Let us see then what observational evidence we have on the effect of volcanic dust on insolation intensity and average temperatures.

"Pyrheliometric records [show] that there was a marked decrease in the insolation intensity from the latter part of 1883 (the year this kind of observation was begun) to and including 1886, from 1888 to 1892, and during 1903. There has also been a similar decrease since about the middle of 1912. Now all these decreases of insolation intensity, amounting at times to 20 per cent of the average intensity, followed violent volcanic eruptions that filled the isothermal region with a great quantity of dust. * * *

"It appears quite certain that volcanic dust can lower the average temperature of the earth by an amount that depends upon the quantity and duration of the dust, and that it repeatedly has lowered it certainly from 1° F. to 2° F. for periods of from a few months to fully three years. Hence it certainly has been a factor, in determining our past climates, and presumably may often be a factor in the production of our future climates. Nor does it require any great volume of dust to produce a marked effect. Thus it can be shown by a simple calculation that less than the one thousandth part of a cubic mile of rock spread uniformly through the upper atmosphere as volcanic dust would everywhere decrease the average intensity of insolation received at the surface of the earth by at least 20 per cent and therefore would, presumably, if long continued, decrease our average temperatures by several degrees. * * * This effect has been clearly traced back to 1750, or to the time of the earliest reliable records. Hence it is safe to say that such a relation between volcanic dust in the upper atmosphere and average temperatures of the lower atmosphere has always obtained, and therefore that volcanic dust must have been a factor, possibly a very important one, in the production of many, perhaps all, past climatic changes" (A: 366–71).

"The intensity of the solar radiation at the surface of the earth depends upon not only the dustiness of the earth's atmosphere but also upon the dustiness, and of course the temperature, of the solar atmosphere. Obviously dust in the sun's envelope must more or less shut in solar radiation just as and in the same manner that dust in the earth's envelope shuts it out. Hence it follows that when this dust is greatest, other things being equal, the output of solar energy will be least,

* A summary paper appeared first, entitled (A) "Volcanic Dust as a Factor in the Production of Climatic Changes," Jour. Washington Acad. Sci., 3, 1913: 365–71. The complete article is (B) "Volcanic Dust and Other Factors in the Production of Climatic Changes, and Their Possible Relation to Ice Ages," Bull. Mt. Weather Observ., Washington, 6, Pt. I, 1913, 1–34.

and that when the dust is least, other things being equal, the output of energy will be greatest. Not only may the intensity of the emitted radiation vary because of changes in the transparency of the solar atmosphere but also because of any variations in the temperature of the effective solar surface which, it would seem, might well be hottest when most agitated, or at the times of spot maxima, and coolest when most quiescent, or at the times of spot minima" (B: 16).

BIOLOGIC EVIDENCE.

In the previous pages there has been presented the evidence for cold climates during geologic time as furnished by the presence of the various tillites. This presentation has also been made from the standpoint of discovery of the tillites, which in general is in harmony with geologic chronology, *i. e.*, the youngest tillites were the first to be observed, while the most ancient one has been discovered recently.

Variability of climate is also to be observed in the succession of plants and animals as recorded in the fossils of the sedimentary rocks. In this study we are guided by the distribution of living organisms and the postulate that temperature conditions have always operated very much as they do now upon the living things of the land and waters. In presenting this biologic evidence we shall, however, begin at the beginning of geologic time and trace it to modern days, for the reason that life has constantly varied and evolved from the more simple to the more complex organisms.

Proterozoic.—The first era known to us with sedimentary formations that are not greatly altered is the Proterozoic, a time of enormous duration, so long indeed that some geologists do not hesitate to say that it endured as long as all subsequent time. These rocks are best known and occur most extensively over the southern half of the great area of 2,000,000 square miles covered by the Canadian shield. There were at least four cycles of rock-making, each one of which, in the area just north of the Great Lakes and the St. Lawrence River, was separated from the next by a period of mountain-making. These mountains were domed or batholithic masses of vertical uplift due to vast bodies of deep-seated granitic magmas rising beneath and into the sediments. In the Grenville area of Canada, Adams and Barlow (1910) tell us that the total thickness of the pre-Proterozoic rocks alone is 94,406 feet, or nearly 18 miles. Of this vast mass more than half (50,286 feet) is either pure limestone, magnesian limestone, or dolomite, and single beds are known with a thickness of 1,500 feet. Certainly so much limestone represents not only a vast duration of time but also warm waters teeming with life, almost nothing of which is as yet known. There is further evidence of life in the widely distributed graphites, carbon derived from plants and animals, which make up from 3 to 10 per cent by weight of the rocks of the Adirondacks (Bastin, 1910). The graphite occurs in beds up to 13 feet thick, and at Olonetz, Finland, there is an anthracite bed 7 feet thick.

It is also becoming plain that there was in the Proterozoic a very great amount of fresh-water and subaërial deposits, the so-called continental deposits, some of which indicate arid climates. Because of the apparent dominance of continental deposits and the great scarcity of organic remains throughout the Proterozoic, Walcott has called this time the Lipalian era (1910: 14).

We have seen that the Proterozoic began with a glacial period, as evidenced by the tillites of Canada, but that this frigid condition did not last long is attested by the younger Lower Huronian limestones of Steeprock Lake, Ontario, having a thickness of from 500 to 700 feet and replete with Archæocyathinæ, coral-like animals up to 15 inches in diameter, and forming reef limestones several feet thick, found there by Lawson and described by Walcott (1912). This discovery is of the greatest value, and opens out a new field for paleontologic endeavor in Proterozoic strata and for philosophic speculation as to the time and conditions when life originated.

We have also seen that the Proterozoic closed with a frigid climate, as is attested by the tillites of Australia, Tasmania, and possibly China, while the other glacial deposits of India, Africa, Norway, and Keweenaw certainly do in part indicate another and older period of cool to cold world climates.

Cambric.—Due to the researches of many paleontologists, but mainly to those of Charles D. Walcott, we now know that the shallow-water seas of Lower Cambric time abounded in a varied animal life that was fairly uniform the world over in its faunal development. It was essentially a world of medusæ, annelids, trilobites, and brachiopods, animals either devoid of skeletons or having thin and nitrogenous external skeletons with a limited amount of lime salts. The "lime habit" came in dominantly much later, in fact, not before the Upper Cambric. However, that the seas in Lower Cambric time had an abundance of usable lime salts in solution is attested by the presence of many Hyolithes, small gastropods and brachiopods, and more especially by the great number of Archæocyathinæ, which made reefs and limestones 200 feet thick and of wide distribution in Australia, Antarctica, California (thick limestones near the base of the Waucoba section), southern Labrador (reefs 50 feet thick), and to a smaller extent in Nevada, New York, Spain, Sardinia, northern Scotland, and Arctic Siberia.

With an abundance of limestone and reef-making animals of world-wide distribution in the Lower Cambric, we must conclude that the climate at that time was at least warm and fairly uniform in temperature the world over. We therefore see the force of a statement made to the writer by Walcott some years ago, in a letter, that "the Lower Cambrian fauna and sediments were those of a relatively mild climate uninfluenced by any considerable extent of glacial conditions," and also that "the glacial climate of late Proterozoic time had vanished before the appearance of earliest Cambrian time."

Toward the close of Lower Cambric time there was considerable mountain-making, without apparent volcanic activity, going on all along eastern North America and to a lesser extent in western Europe. These uplifts seemingly had much effect upon the marine life, for the Middle Cambric faunas became more and more provincial in character in comparison with the earlier, more cosmopolitan faunas of Lower Cambric time.

The Archæocyathinæ, which had endured since earliest Proterozoic time, now vanished, and their extinction is suggestive of cooler waters; there was, however, a greater variety of invertebrate forms, more lime-secreting invertebrates, and far more widespread limestone deposition in Middle Cambric time. In the Upper Cambric the brachiopods, gastropods, cephalopods, and bivalve crustaceans were abundantly represented by thick-shelled forms, and in most places throughout North America there was marked deposition of limestones, magnesian limestones, and dolomites, all of which is suggestive of warmer waters.

Ordovicic and Siluric.—The Ordovicic seas from Texas far into the Arctic regions were dominated by limestone deposits and a great profusion of marine life that was also more highly varied than that of any earlier time. The same species of graptolites, brachiopods, bryozoans, trilobites, and other invertebrate classes had a very wide distribution, all of which is evidence that at that time the earth had mild and uniform climates. In the Middle Ordovicic and again late in that period reef corals were common from Alaska to Oklahoma and Texas (Vaughan, 1911).

Toward the close of the Ordovicic, mountain-making was again in progress throughout eastern North America without significant volcanic activity, but in western Europe, where the movements were less marked, volcanoes were more plentiful. The seas were then almost completely withdrawn from the continents, and yet when the Siluric waters again transgressed the lands we find not only the same great profusion and variety of life as before, but as widely extended limestone deposition. The evidence is again that of mild and uniform climates. We can therefore say that the temperatures of air and water had been mild to warm throughout the world since the beginning of Cambric time; that there was a marked increase of warmth in the Upper Cambric; and that these conditions were maintained throughout the Ordovicic and the earlier half of the Siluric, since shallow-water corals, reef limestones, and very thick dolomites of Siluric time are as common in Arctic America as in the lower latitudes of the United States or Europe.

The Siluric closed with an epoch of sea withdrawal and North America was again arid, for now red shales, gypsum, thick beds of salt, and great flats of sun-cracked water-limestone were the dominant deposits of the vanishing seas. The marine faunas were as a rule scant and the individuals generally under the average size. In North America no marked mountain-making was in progress, but all along western Europe, from Ireland and Scotland across Norway into far Spitzbergen, the Caledonian Mountains were rising. In eastern Maine throughout Middle and Upper Siluric time there were active volcanoes of the explosive type, for here occur vast deposits of ash.

Devonic.—In the succeeding Lower Devonic time the Caledonian intermontane valleys of Scotland and north to at least southern Norway were filling with the Old Red sandstone deposits of a more or less arid climate. On the other hand, the invading seas of northern Europe were small indeed, and their deposits essentially sandstones or sandy shales, but in southern Europe and North America, where the invasions were also small and restricted to the margin of the continent, the deposits were either limestones or calcareous shales. The life of these waters was quite different from that of the earlier and Middle Siluric, and entire stocks had been blotted out in later Siluric time, as is seen best among the graptolites, crinids, brachiopods, and trilobites, while new ones appeared, as the goniatites, dipnoans or lung-fishes, sharks, and the terrible armored marine lung-fishes, the arthrodires.

From this evidence we may conclude that the early Paleozoic mild climates were considerably reduced in temperature toward the close of the Siluric and that even local glaciation may have been present. Refrigeration may have been greatest in the southern hemisphere, where the marine formations of Devonic time are coarse in character and, in Africa, of very limited extent. Corals were scarce or absent here, and in South Africa the glacial deposits of the Table Mountain series may be of late Siluric age; if so, they harmonize with the Caledonian period of mountain-making in the northern hemisphere. Warmer conditions again prevailed in the latter hemisphere early in Middle Devonic times, for coral reefs, limestones, and a highly varied marine life with pteropod accumulations were of wide distribution. On Bear Island workable coal beds were laid down in late Devonic time.

Throughout the Devonic, but more especially in the Lower and Middle Devonic, the entire area of the New England States and the Maritime Provinces of Canada was in the throes of mountain-making, combined with a great deal of volcanic activity. At the same time, many volcanoes were active throughout western Europe.

Carbonic.—The world-wide warm-water condition of the late Devonic seas of the northern hemisphere was continued into those of the Lower Carbonic. These latter seas were also replete with a varied marine life, among which the corals, crinids, blastids, echinids, bryozoans, brachiopods, and primitive sharks played the important rôles. Limestones were abundant and with the corals extended from the United States into Arctic Alaska. Reefs of Syringopora are reported in northern Finland at 67° 55′ N., 46° 30′ E., on Kanin Pensinula (Ramsay). Even several superposed coal beds, and up to 4 feet in thickness of pure coal, of early Lower Carbonic age, occur at Cape Lisburne, overlain by Lower Carbonic limestones with corals. It is generally held that the world climate at this time was uniformly mild and the many hundred kinds of primitive sharks lead to the same conclusion. There were in the American Devonic 39 species of these sharks, in the Lower Carbonic not less than 288, in the Coal Measures 55, and in the earliest Permic only 10. They had no enemies other than their own kind to fear, and as the same rise and decline occurred also in Europe, we must ask ourselves what was the cause for this rapid dying-out of the ancient sharks during and shortly after early Coal Measures time. With the sharks also vanished most of the crinids, but otherwise there was an abundance and variety of marine life (wide distribution of large foraminifers) with much limestone formation. The vanishing of the sharks does not appear therefore to have been due solely to a reduction of temperature, but may have been further helped by the oscillatory condition and retreat of the late Lower Carbonic seas.

Toward the close of the Lower Carbonic, or after the Culm and its coals of western Europe had been laid down, mountain movements on a great scale began to take place in central Europe, and then were born the Paleozoic Alps of that continent. These mountains, Kayser tells us, were in constant motion but with decreasing intensity throughout the Upper Carbonic, culminating in "a mighty chain of folded mountains." Toward the close of the Upper Carbonic began the rise of the Urals, which was finished in late Permic time when the Paleozoic Alps of Europe were again in motion. These movements are also traceable in Armenia and others are known in central and eastern Asia. Likewise, in America, the southern Appalachians were in movement at the close of the Lower Carbonic, but the greatest of all of the Upper Carbonic thrustings began to take place at the close of the period and culminated apparently in the earlier half of Permic time, when the entire Appalachian system from Newfoundland to Alabama, and the Ouachita Mountains, extending through Arkansas and Oklahoma, arose as majestic ranges anywhere from 3 to 4 miles high.

These mountain-making movements of long duration at first caused the oceans to oscillate frequently back and forth over parts of the continents, and great brackish-water marshes were developed, producing the greatest marsh floras and the greatest accumulations of good coals that the world has had. The paleobotanists White and Knowlton tell us that the climate of Upper Carbonic time was relatively uniform and mild, even subtropical in places, accompanied by high humidity extending to or into the polar circles. Plant associations were then "able to pass from one high latitude to the opposite without meeting an efficient climatic obstruction in the equatorial region" (1910: 760).

The marine faunas of Upper Carbonic time were fairly uniform in development, and many species had a wide distribution, although the biotas were still somewhat provincial in character. Limestones or calcareous shales predominated. The large Protozoa of the family Fusulinidæ occurred throughout the northern hemisphere and less widely in South America. They were also very common in Spitzbergen. Staff and Wedekind (1910) state that the Fusulinidæ occur here in a black asphaltic calcareous rock, *i. e.*, a sapropel like those now forming in marine tropical regions, according to Potonié. The water, they state, was shallow, highly charged with calcium carbonate and of a tropical character, or at the very least not cooler than that of the present Mediterranean. The very large insects of the Coal Measures tell the same climatic story, for Handlirsch (1908: 1152) says that the cockroaches of that time were as long as a finger and the libellids as long as an arm. They were "brutal robbers" and scavengers living in a tropical and subtropical climate, or at the very least in a mild climate devoid of frosts. We therefore conclude that after Middle Devonic time the climate of the world was as a rule uniformly warm and more or less humid and that it remained so to the close of Upper Carbonic time.

During the time of these mild and humid climates vast accumulations of carbon extracted by the plants out of the atmosphere were being stored up in brackish and fresh-water swamps, and even greater quantities of this element were being locked up in the limestones and calcareous shales in the seas and oceans. According to the physico-chemist Arrhenius, and many geologists and paleontologists, so much loss of carbon dioxide and its associated water vapor from the air must have thinned the latter greatly and thus largely reduced the atmospheric blanket and retainer of the sun's heat rays. Therefore they hold that these factors alone were sufficient to have brought on a glacial climate. It may be that this theory will not stand the test of time, but even so we have learned that in Carbonic times there were earth movements on so grand a scale as to be but slightly inferior to those of the late Tertiary that were followed by the Pleistocene glacial climate.

Permic.—Very early in Permic time the mild climate of the past was greatly changed; the evidence is now overwhelming that throughout the southern hemisphere there was a glacial period seemingly of even greater extent than that of the northern hemisphere during the Pleistocene. This evidence is most easily seen in the wide distribution of the tillites and the scratched and polished grounds over which the land ice moved in Africa, Australia, Tasmania, India, and South America. In the northern hemisphere the evidence of ice work is far less marked; but tillites occur near Boston, Massachusetts, and in the Urals, and there is much evidence of thin and arid climates, seen in the widely distributed red formations. Then, too, the land life of this time clearly indicates that a great climatic change had taken place in the environment of the organic world.

The grand cosmopolitan swamp floras of the Upper Carbonic, consisting in the main of spore-bearing plants, such as the horse-tails (Equisetales), the running pines, and club-mosses (Lycopodiales), and the ferns, among which were also many broad-leaved evergreens (Cordaites) and seed-bearing ferns (Cycadofilices), were very largely exterminated in the southern hemisphere at the beginning of Permic time. In the northern hemisphere, however, the older flora maintained itself for a while longer, as best seen in North America, but finally the full effects of the cooled and glacial climates were felt everywhere. Then in later Permic time the old floras completely vanished, except the hardier pecopterids, cycads, and conifers of the northern hemisphere, and with these latter mingled the migrants from the hardy Gangamopteris flora originating in the glacial climate of the southern hemisphere (White, 1907). Some of the trees show distinct annual growth rings, and hence the presence of winters. It was these woody floras that gave rise to the cosmopolitan floras of early Mesozoic time.

With the vanishing of the cosmopolitan coal floras also went nearly all of the Paleozoic insect world of large size and direct development, for the insects of late Permic time were small and prophetic of modern forms. Then, too, they all passed through a metamorphic stage indicating, according to Handlirsch, that the insects of earlier Permic time had learned how to hibernate through the winters in the newly originated larval conditions.

Our knowledge of the land vertebrates of late Paleozoic time is increasing rapidly and it is becoming plainer that great changes were also in progress here. The vertebrates of the Coal Measures, either the armored amphibians (Stegocephalia) or the primitive reptiles, were still largely addicted to the "water habit" and lived in fresh waters or swamps, but this was much changed by the arid climates and vanishing swamps of later Permic times, and in the Triassic we meet with the first truly terrestrial reptilian faunas.

A climatic change naturally must affect the land life more quickly and profoundly than that of the marine waters, for the oceanic areas have stored in themselves a vast amount of warmth that is carried everywhere by the currents. The temperature of the ocean is more or less altered by the changes of climate, be they of latitude or of glaciation. The surface temperatures in the temperate and tropical regions, however, are the last to be affected, and only change when all of the oceanic deeps have been filled with the sinking cold waters brought there by the currents flowing from the glaciated area. We therefore find that the marine life of earlier Permic time was very much like that of the Coal Measures, and that it was not profoundly altered even in the temperate zones of Middle Permic time (Zechstein and Salt Range faunas). Our knowledge of Upper Permic marine life is as yet very limited and will probably always remain so because of the world-wide subtraction of the seas from the lands at that time. It was a period of continued arid climates, and the marginal shallow sea pans were, as a rule, depositing red formations with gypsum, and locally, as in northern Germany, alternations of salt with anhydrite or polyhalite in thicknesses up to 3,395 feet. In certain of these zones there were developed annual rings so regular in sequence as to lead to the inference that they were the depositions of warm summers and cold winters, enduring for at least 5,653 years (Görgey, 1911).

Triassic.—When we examine into the Triassic faunas we meet at once with a wholly new marine assemblage. The late Paleozoic world of fusulinids, tetracorals, crinids, brachiopods, nautilids, and trilobites had either vanished or was represented by a few small and rare forms. On the other side, in the Triassic, their places were taken by a rising marine world of small invertebrates, now hexacorals, regular echinids, modern bivalves (among them the oysters), siphonate gastropods, and more especially by a host of ammonites and a prophecy of the coming of squids and marine reptiles. Truly, there is no greater change recorded in all Historical Geology!

Plants are scarce in the rocks of Triassic time until near its close in the Rhætic, when we can again truly speak of Triassic floras. These are known from many parts of the world, and according to Knowlton there is nothing in the floras to suggest a "depauperate and pinched" condition, as has often been said. "In North Carolina, Virginia and Arizona, there are trunks of trees preserved, some of which are 8 feet in diameter and at least 120 feet long, while hundreds are from 2 to 4 feet in diameter. Many of the ferns [some are tree ferns] are of large size, indicating luxuriant growth, while Equisetum stems 4 to 5 inches in diameter are only approached by a single living South American species. * * * The complete, or nearly complete absence of rings in the tree trunks indicates that there were no, or but slight, seasonal changes due to alterations of hot and cold, or wet and dry periods." On the whole, the climate was "warm, probably at least subtropical" (1910A: 200–2).

Of insects, too few species (27) are known to be of value for climatic deductions. On the other hand, the reptilian life of the Triassic in America, Africa, and Europe was highly varied, and with the dinosaurs dominant and often of large size again gives evidence that appears to be indicative of uniform and mild climate.

The marine Triassic deposits consisted largely of thick limestones, and such are well developed in Arctic America and Arctic Siberia. One of the oldest faunas, known as the Meekoceras fauna, has a very great distribution from Spitzbergen to India and Madagascar, and from Siberia at Vladivostok to California and Idaho. In general, however, the Triassic assemblages were more provincial, and it was not until middle and late Triassic time that the faunas again had wide distribution. Limestones with thick coral reefs, of the same age, appear in the Alps (up to 1,000 meters thick), India, California, Nevada, Oregon, and Arctic Alaska. Smith, from whom most of these facts were taken, states that this shows there was during the Triassic "nearly uniform distribution of warm water over a great part of the globe" (1912A: 397–8).

We may therefore conclude that the rigid climate of the Permic had vanished even before the earliest of Triassic times, and that the climate of the latter period until near its close was again mild and fairly uniform though semiarid or even arid the world over.

Late Triassic-Lias.—Throughout much of late Triassic time there was renewed crustal instability, for we have the evidence of volcanism on a great scale all along the Pacific from central California into far Alaska, in eastern North America from Nova Scotia to Virginia, in Mexico, South America (in southern Brazil 600 meters thick), and New Zealand. The volcanoes of western North America were probably insular in position, for their lavas and ash beds are found interbedded with marine sediments. Just how important this movement was and what effect it had upon the climate is not yet clear, but there is important organic evidence leading to the belief that the temperature was considerably reduced during latest Triassic and earliest Jurassic time.

Pompeckj, Buckman, and Smith state that late Triassic time was a particularly critical one for the ammonites. Of the far more than 1,000 known species of Triassic ammonites, not one passed over into the Jurassic, and but a single family survived this time, the Phylloceratidæ. Pompeckj says that "out of Phylloceras has developed the abundance of Jurassic-Cretaceous ammonites" (1910: 64), while Buckman holds it was out of Nannites by way of the Liassic Cymbites that the later fullness of ammonite development came.

In the Liassic there are now known 415 species of insects that remind one much of modern forms. Nearly all were dwarf species, smaller than similar living insects of the same latitude and far smaller than Paleozoic or Upper Jurassic insects. Handlirsch (1910B) is positive that this uniform dwarfing of the Liassic insects was due to a general reduction of the climate and that the temperature was then cool and like that of present northern Europe between latitudes 46° and 55°. The climate, he states, was certainly cooler than either that of the Middle Triassic or Upper Jurassic.

In this connection we must not overlook the fact that the known Liassic insects are of wide distribution, for 172 species are known from England, 164 from Mecklenburg, northern Germany, 75 from Switzerland, and 2 from upper Austria. With this depauperating of the insects and the vanishing of the late Triassic ammonites, there is also to be noted a marked quantitative reduction and geographic restriction among the reef corals of Liassic time We therefore are seemingly warranted in concluding that the cooling of the climate in late Triassic and early Jurassic time was not local in character, but was rather of a general nature. Much workable coal was also laid down in Liassic time, not only in Hungary but also in many places eastward into China and Japan. In addition, the many black shales of this time furnished further evidence of cool and non-tropical climates; coal and black shales are so general in occurrence throughout the Liassic rocks that the time is often referred to as the Black Jura. Finally, certain Liassic conglomerates of Scotland have been thought by some to be of glacial origin (J. Geikie).

Jurassic.—The Jurassic formations of Europe are so rich in fossils that they have been the classic ground on which many paleontologists and stratigraphers were reared. From the studies of these faunas came the first clear ideas of climatic zones and world paleogeographic maps through the work of the great Neumayr of Vienna. As the result of a very long study of the ammonites and their geographic distribution, he came to the conclusion in 1883 that the earth in Jurassic time had clearly marked equatorial, temperate, and cool polar climates, agreeing in the main with the present occurrence of the same zones. He also said that "the equator and poles could not have very much altered their present position since Jurassic times." His conclusions were, however, assailed by many, and while no one has greatly altered his geographic belts of ammonite distribution, still the consensus of opinion to-day is that these are representative rather of faunal realms than of temperature belts. On the other hand, it is admitted that there were then clearly marked temperature zones—that is, a very wide medial warm-water area, embracing the present equatorial and temperate zones, with cooler but not cold water in the polar areas. That the oceanic waters of Middle and (somewhat less so) of Upper Jurassic times were warm throughout the greater part of the world is seen not only in the very great abundance of marine life—probably not less than 15,000 species are known in the Jurassic—but also in the far northern distribution of many ammonites, reef corals, and marine saurians. The Jurassic often abounds in reefs made by sponges, corals, and bryozoans. Jurassic corals occur 3,000 miles north of their present habitats.

The Jurassic floras were truly cosmopolitan, and Knowlton tells us that of the North American species, excluding the cycad trunks, about half are also found in Japan, Manchuria, Siberia, Spitzbergen, Scandinavia, or England. "What is even more remarkable, the plants found in Louis Philippe Land, 63° S., are practically the same [both generically and specifically] as those of Yorkshire, England. * * * The presence of luxuriant ferns, many of them tree ferns, equisetums of large size, conifers, the descendants of which are now found in southern lands, all point to a moist, warm, probably subtropical climate" (1910A: 204–5). The insects of this time were again large and abundant, indicating a warm climate—evidence in harmony with the plants.

At the close of the Jurassic the Sierra Nevadas of California and the Humboldt Ranges of Nevada were elevated; probably also the Cascade and Klamath Mountains farther north;

but this disturbance seemingly had no marked effect upon the world's climate, though there was a considerable retreat of the seas from the continents.

Cretacic.—The emergence of the continents at the close of the Upper Jurassic gave rise to extensive accumulations of fresh-water deposits, known in western Europe as the Wealden, and in the Rocky Mountain area of North America as the Morrison. These are now regarded as of Lower Cretacic (more accurately Comanchic) age. Along the Atlantic border of the United States occur other continental deposits, known as the Potomac formations, in the upper part of which the modern floras or Angiosperms make their first appearance. Before the close of the Lower Cretacic this early hardwood forest had spread to Alaska and Greenland, where elms, oaks, maples, and magnolias occurred. Knowlton concludes from this evidence that the climate "was certainly much milder than at the present time" and "was at least what we would now call warm temperate" (1910A: 205–6). It was therefore a climate somewhat cooler than that of the Jurassic. On the other hand, the Neocomian series of King Karl's Land has silicified wood, the trunks of which, according to Nathorst, are at least 80 cm. in diameter and show 210 annular rings. These rings are far better developed than in stems of the same age found in Europe, "which indicates that the trees lived in a region where the difference between the seasons was extremely pronounced" (1912: 339).

At this time, in the temperate and tropical belts, the world had the greatest of all land animals, the dinosaurs, reptiles attaining a length in North America of 75 feet or more and in equatorial German East Africa of probably 125 feet. Their bones range to 50° N. latitude, and the animals must have lived in a fairly warm and moist climate.

While the Lower Cretacic seas were prolific in life, the most characteristic shellfish of southern Europe, the Mediterranean countries, and Mexico, were the limestone-making rudistids, large ground-living foraminifers (Orbitolina), and reef corals. In northern Europe and in the United States from southern Texas to Kansas, nothing of these warm-water faunal elements is known. It is recognized that the north European seas had Arctic connections by way of Scandinavia and Russia, and along the west coast of North America are seen many other boreal migrants as far south as California and even Mexico. These waters, however, were not cold. The same geographic distribution prevailed in the Upper Cretacic of Europe. This distribution was first noted in Texas by Ferdinand Roemer in 1852, and he further observed that "in each case the European deposit is approximately 10° farther north than its American analogue," and concluded "that the differences between the northern and southern facies were due to climate and that the climatic relations between the two sides of the Atlantic were about the same in Cretaceous time as they are now" (Stanton, 1910: 67). Even though Roemer's conclusion as to climatic zones was founded on erroneous stratigraphic correlations, still his theory has long been looked upon favorably, but in 1908 Gothan showed that the fossil woods of the late Upper Cretacic of central Germany have distinct annual rings, while those of Egypt do not have a trace of them. The late Cretacic woods of Spitzbergen also have decided growth rings. Berry (1912) states that the climate of Upper Cretacic time was far more uniform than now and that there was an increase of warmth southward, Alabama having then a climate that was subtropical or even tropical. On the other hand, the early Upper Cretacic or Cenomanian flora of Atane in western Greenland, according to Nathorst, "is particularly rich in the leaves of Dicotyledonous trees, among which are found those of planes, tulip trees, and bread fruits, the last mentioned closely resembling those of the bread-fruit tree (*Artocarpus incisa*) of the islands of the southern seas" (1912: 340).

In Middle Cretacic times the oceans began again to spread over the continents and this transgression of the seas was one of the greatest of the geologic past. It is interesting to note that even though there was great opportunity for expansive evolution, but few new marine stocks appeared here, and it was rather a time of death to many characteristic stocks. This well-known fact is clearly brought out by Walther in his interesting book, "Geschichte der Erde und des Lebens" (1908), in Chapter 26, entitled "Cretaceous time and its great mortality." Entire stocks of specialized forms vanished, just as did other stocks at the close of the Paleozoic. In late Cretacic time it was the ammonites, belemnites, the rudistids that began to develop in great numbers in the Lower Cretacic, and the other thick-shelled large bivalves (Inoceramus) that perished. In addition, there was a great reduction among the reef corals, the replacing of the dominant ganoids by the teleosts or bony fishes, and, finally, the complete dying out of the various stocks of marine saurians.

On the land, with the further rise of the Angiosperm floras, we see the vanishing of the reptilian dragons known as pterodactyls, and, at the very close of the Cretacic, the last of the large and small dinosaurs and the birds with teeth. "We thus see the reptiles displaced from the seas by the fishes; on the land they are restricted by the rise of the mammals, in the air after a short struggle by the more finely organized birds—in short, the reptilian dominance is destroyed with the end of the Mesozoic era, in which entire time they were the characteristic feature " (Koken, 1893: 436).

The Upper Cretacic was therefore a time of great mortality among animals, "here sooner, there later; although numerous relict faunas are preserved for a time and last into the Cenozoic, still there never was so great a mortality as that taking place toward the close of the Cretacic" (Walther, 1908: 449).

During the Upper Cretacic, but more especially toward the close of the period, mountain-making on a vast scale went on, along with exceptional outpourings of lavas and ashes. These movements, though of less intensity, were repeated in early Tertiary times, and while they were equaled only by those of the closing period of the Paleozoic, they were exceeded by the crustal deformation of late Tertiary time; they form the Laramide revolution of Dana, embracing the mountains of western North and South America from Cape Horn to Alaska and the reëlevation of the Appalachian and Antillean Mountains. Throughout the Eocene in the Rocky Mountains there were many volcanoes throwing out immense quantities of ashes in which is entombed a remarkable vertebrate fauna. Then in late Cretacic time in peninsular India occurred the Deccan lava flows, the most stupendous eruptions known to geologists, covering an area of 200,000 square miles, in thickness anywhere up to a mile or more.

Although there were these great crustal movements toward the close of the Upper Cretacic, nevertheless they seem to have had no marked effect on the climates of the world, for nowhere has anyone shown the presence of unmistakable glacial tills of this age.* Then, too, the floras of early Tertiary times are said to be of about the same character as those of the late Cretacic and they indicate that the climates were warm with slight latitudinal variation, so slight that even in Greenland and Spitzbergen the early Tertiary floras were those of a moist and mild climate.

Tertiary.—We have seen that there was no marked climatic change in the time from the Cretacic to the Eocene, but that there was a reduction in temperature is admitted by paleobotanists and students of marine life. Berry states that the Middle Eocene floras of Europe "show many tropical characters absent in the earlier Eocene" (1910: 205). The Oligocene marine faunas were prolific in species, and the largest of all foraminifers, the nummulites, although still present at this time, had their widest distribution and largest species in the Middle Eocene and especially in the Tethyian Sea of the Old World, extending from 20° S. to 20° N. latitude (Stromer, 1909: 42).

In Miocene time on Spitzbergen (Cape Staratschin) lived the swamp cypress (*Taxodium distichum miocenum*), a leafy sequoia, pines and firs, besides various hardwood trees, such

* At the Princeton meeting of the Geological Society of America, December 29, 1913, Professor W. W. Atwood announced the discovery of a tillite about 90 feet thick in the San Juan Mountains of southwestern Colorado. The age of these glacial deposits is somewhere between late Cretacic and late Eocene. We therefore are now on the road to finding the physical evidence of a reduced climate during or following the close of the Laramide revolution.

as poplars, birches, beeches, oaks, elms, magnolias, limes, and maples. The swamp cypress, Nathorst says, "formed forests, as in the swamps in the southern portion of the United States. This conclusion is also confirmed by the occurrence of the remains of rather numerous insects" (1912: 341). All of the plants mentioned then flourished as far north as 79° N. latitude, and even at nearly 82° in Grinnell Land. This is evidence that in early Miocene time the climate was at least warm-temperate in Arctic America.

Again, Dall (1895) states that in Middle Miocene time considerable reduction of the climate appeared, for the Atlantic Chesapeake faunas were those of temperate waters and they spread southward as far as the eastern area of the Gulf of Mexico. Similar conditions are noted by the same conchologist in the northern Pacific Ocean. He says:

"The conditions indicated by the faunas of the post-Eocene Tertiary on the Pacific Coast from Oregon northward are a cool temperate climate in the early and Middle Miocene, a warming up toward the end of the Miocene culminating in a decidedly more warm-water fauna in the Pliocene, and a return to cold if not practically Arctic temperatures in the Pleistocene" (1907: 457-8).

The Tertiary was an era of extraordinary crustal movements, finally resulting in the greatest mountain chains of all geologic time. These movements began in early Eocene time in the Rocky Mountains and at the close of this epoch further deformation took place in the Klamath and Coast Ranges of Oregon and the Santa Cruz Mountains of California. In Europe the elevations of Tertiary time started at the close of the Eocene in the Pyrenees, and in the Miocene the entire "Alpine system" was in elevation. This unrest spread at the same time to the Caucasus, Asia, and to the entire Himalayan region of highest mountains and elevated plateaus, an area 22° of latitude in width. It is probable that all of the world's great mountain chains were more or less reëlevated in Miocene and Pliocene times, resulting in the present abnormally high stand of the continents when contrasted with the oceanic mean level.

These elevations also altered the continental connections, for North and South America were reunited in Miocene times, and western Europe, Greenland, and America were severed late in the Tertiary era, the exact time being as yet not clearly established. With these great changes also must have come about marked alterations in the oceanic currents and, as a consequence, in the distribution of heat and moisture over vast areas of the northern Atlantic lands. It is admitted by all paleontologists that the marine waters of late Pliocene times in the Arctic region were cool, and the widespread glacial tills of the northern hemisphere are evidence of a glacial climate of varying intensity throughout Pleistocene time.

CONCLUSIONS.

Our studies of the paleometeorology* of the earth are summed up in figure 90. We have seen that two marked glacial periods are clearly established. The one best known was of Pleistocene time and the other, less well known in detail, of earliest Permic time. Both were world-wide in their effects, reducing the mean temperatures sufficiently to allow of vast accumulations of snow and ice, not only at high altitudes, but even more markedly at low levels, with the glaciers in many places attaining the sea. We also learn that the continental glaciers of Pleistocene time were dominant in the polar regions, while those of Permic time had their greatest spread from 20° to 40° south of the present equator, and to a far less extent between 20° and 40° in the other hemisphere. There is also some evidence of glaciers in equatorial Africa in Permic time. We may further state that, although Pleistocene glaciation was general in the Arctic region, there certainly was none at this pole in early Permic time, because of the widespread and abundant marine faunas that are not markedly unlike those of the Upper Carbonic; as for the south pole, our knowledge of pre-Pleistocene glaciation is as yet a blank.

* H. F. Osborn, Compte Rendu, Congrès Internat. Zool., Berne, 1904, 1905: 88. For a review of the papers treating of paleometeorology, see M. Semper, Geol. Rundschau, I, 1910: 57-80.

A glacial period does not appear to remain constantly cold, but fluctuates between cold glacial climates and warmer interglacial times of varying duration. During the Pleistocene there were, according to the best glaciologists, at least three, if not four, such warmer intervals. The Permic glacial period also had its warmer times, while the interbedded red strata of the Proterozoic tillites seem to point to the same variability. It is this decided temperature fluctuation during the glacial periods that is so very difficult to explain.

In addition to the well-known Pleistocene and Permic glaciation, there is rapidly accumulating a great deal of evidence to the effect that there were at least two and probably three other periods of widespread glacial climates. All of these were geologically very ancient, earlier than the Paleozoic; in fact, one was at or near the close of Proterozoic time,

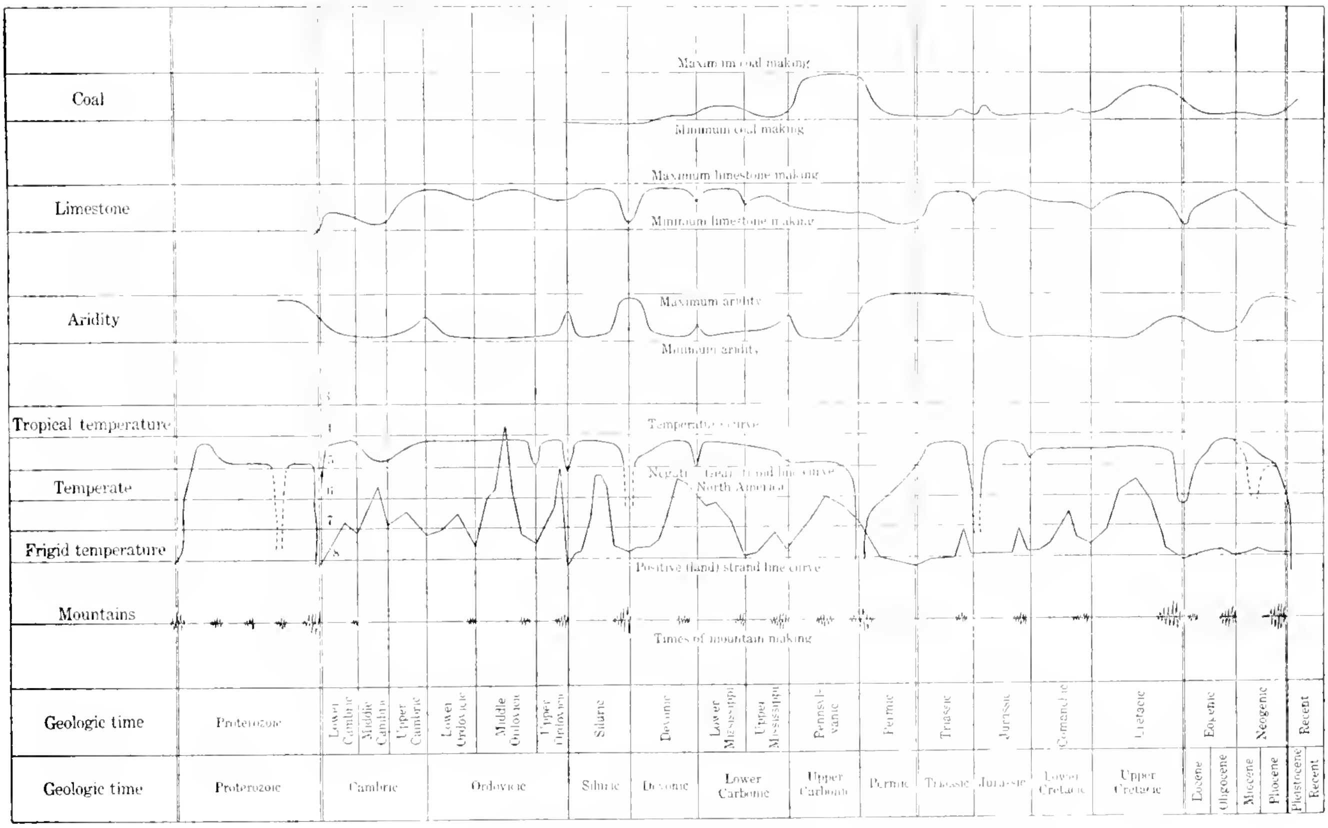


FIG. 90.—Chart of Geological Climates. Paleometeorology.

while another was at the very beginning of that era and almost at the beginning of earth history as known to geologists.

The oldest of all glacial materials occurs at the base of the Lower Huronian and is of great extent in Canada. Seemingly of the same time is the Torridonian glacial testimony of northwest Scotland. The Proterozoic tillites of China in latitude 31° N. may also be of this time. If these correlations are correct, then the oldest glacial evidence indicates that a greatly cooled climate prevailed near the very beginning of the known geologic record and that it was dominant in the northern hemisphere.

Toward or at the close of the Proterozoic there is other evidence of a glacial climate in Australia, Tasmania, and Norway. These occurrences of tillites lie immediately beneath Lower Cambric fossiliferous marine strata and probably are of pre-Cambric age.

In India there is also evidence of late Proterozoic tillites in two widely separated places, and it may be that the inadequately studied Keweenawan testimony of the Lake Superior region is of this time. If so, these occurrences record a distribution of glacial materials very similar to that of Permic time. Again, the Proterozoic tillites of Africa are clearly of another age, so that there is evidence of at least three periods of glaciation previous to the Paleozoic.

The physical evidence of former glacial climates is even yet not exhausted, for the Table Mountain tillites of South Africa point to a cold climate that apparently occurred, at least locally, late in Siluric time. Finally, there may have been a seventh cool period in early Jurassic time (Lias), but the biologic evidence so far at hand indicates that it was the least significant among the seven probable cool to cold climates so far discovered in the geologic record.

The data at hand show that the earth since the beginning of geologic history has periodically undergone more or less widespread glaciation and that the cold climates have been of short geologic duration. So far as known, there were seven periods of decided temperature changes and of these at least four were glacial climates. The greatest intensity of these reduced temperatures varied between the hemispheres, for in earliest Proterozoic and Pleistocene time it lay in the northern, while in late Proterozoic and Permic time it was more equatorial than boreal. The three other probable periods of cooled climates are as yet too little known to make out their centers of greatest intensity.

Of the four more or less well-determined glacial periods, at least three (the earliest Proterozoic, Permic, and Pleistocene) occurred during or directly after times of intensive mountain-making, while the fourth (late Proterozoic) apparently also followed a period of elevation. The Table Mountain tillites of South Africa, if correctly correlated, fall in with the time of the making of the great Caledonian Mountains in the northern hemisphere. On the other hand, the very marked and world-wide mountain-making period, with decided volcanic activity, during late Mesozoic and earliest Eocene times, was not accompanied by a glacial climate, but only by a cooled one. The cooled period of the Liassic also followed a mountain-making period, that of late Triassic time. We may therefore state that cooled and cold climates, as a rule, occur during or immediately follow periods of marked mountain-making—a conclusion also arrived at independently by Ramsay (1910: 27).

Geologists are beginning to see clearly that the lands have been periodically flooded by the oceans, and the times of maximum submergence and emergence of the continents since earliest Paleozoic time are fairly well known. The two marked glacial periods since Cambric time (Permic and Pleistocene) and the three other more or less cooled climates (late Siluric, Liassic, and late Cretacic) all fall in with the times when the continents were more or less extensively and highly emergent. There were no cold climates when the continents were flooded by the oceans, and it may be added that the periods of widespread limestone-making preceded and followed, but did not accompany, the reduced climates. On the other hand, the periods of greatest coal-making (Upper Carbonic and Upper Cretacic) accompanied the time of greatest continental flooding and preceded the appearance of cooled climates.

The more or less coarse red sediments seen at many horizons of the geologic column are interpreted as the deposits of variably arid climates, or those that are alternately wet and dry. In the Paleozoic they are seen more often at the close of the periods when the seas were temporarily withdrawn and the lands were most extensive. These red deposits alternate with formations that are either wholly marine or of brackish-water origin, and in the latter case of gray, green, blue, or black color.

Humphreys has shown that volcanic dust in the isothermal region of the earth's atmosphere does appreciably reduce the temperature at the surface of the globe. It is thought that if explosive volcanoes continued active through a more or less long geologic time, this factor alone would bring on, or largely assist in bringing on, a more reduced temperature or even a glacial climate. If then, we may further postulate that volcanic activity is most marked during times of mountain-making, *i. e.*, during the "critical periods" at the close of the eras and the less violent movements at the close of the periods, we should expect ice ages, or at least considerably cooled climates, occurring here also. Let us see how the facts agree with this hypothesis.

Of the "critical periods" at the close of the Paleozoic, Mesozoic, and Cenozoic eras, we know that the first and last were accompanied by glacial climates, but the Mesozoic, though a time of very extensive mountain-making and great and prolonged volcanic activity in North America, did not close with a glacial, but only with a slightly cooled climate. Not only this, but we find that volcanism was renewed in the Cordilleras of North America throughout much of the Eocene, and yet there was developed no glacial climate at this time.* In the same way the marked temperature reduction at the close of the Cenozoic in the Pleistocene was subsequent to the Miocene and Pliocene movements of this period and not coincident with them, while that of the Paleozoic appears to fall in with the rise of the Urals and Appalachians, though but little volcanism seems to have accompanied the movements in North America. It should also be said that equally extensive movements were going on in Europe in the rise of the European Alps during the geologic times before and after the Permic glaciation, and that the earlier movements did not appreciably affect the climate.

Again, there was decided mountain-making toward the close of the Siluric in the formation of the Caledonian Mountains all along western Europe from Spitzbergen to Scotland, with marked volcanic extrusions during the Siluric and early Devonic in Maine, the Maritime Provinces of Canada, and Europe. Yet we have no glacial climate at these times, certainly not in the northern hemisphere; rather it seems that the temperature was mild the world over. It is possible, however, that the Table Mountain tillites of South Africa may coincide with this time, and if so a colder temperature affected the southern hemisphere only locally.

On the other hand, the "life thermometer" indicates a cooled period at the close of the Triassic and the following Liassic, but this reduction of temperature, again, is geologically subsequent to, rather than coincident with the marked volcanic activity of the Triassic in many widely separated places.

Finally, there were earth movements of considerable magnitude at the close of theLower Cambric, Ordovicic, and Jurassic that were not accompanied by glacial climates. At all of these times there appears, however, to have been a drop in temperature, slight for the two first-mentioned periods and more marked for the third one, for here we find in the austral region, during earliest Cretacic times, winters alternating with summers.

We may therefore conclude that volcanic dust in the isothermal region of the earth does not appear to be a primary factor in bringing on glacial climates. On the other hand, it can not be denied that such periodically formed blankets against the sun's radiation may have assisted in cooling the climates during some of the periods when the continents were highly emergent.

It has long been known that during times of intensive mountain-making and more or less cooled climates there was great destruction and alteration of life. The first effects of the environmental changes occurred among the organisms of the land, while the climax of alteration among the marine life appeared later. This is especially well seen in the Permic glaciation, which first blotted out the cosmopolitan Upper Carbonic flora and the insects, while the life of the sea continued without marked change into Middle Permic time. In the later Permic, in the northern equatorial waters of Tethys, occurred the final destruction of many stocks that had long dominated the Paleozoic seas. The explanation of these facts appears to be that on the lands the change of climate takes immediate effect on the organisms, while in the oceans a longer time is consumed in cooling down the warm and

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* See footnote, page 283.

equable temperature and in filling all the basins with cold water. Accordingly the last regions in the oceans to come under the influence of glacial climates must be the shallow waters of the equatorial area. The proof of this conclusion is seen in that the last stand made by the marine Paleozoic world is recorded in the deposits of Tethys, the great Mediterranean sea of Permic time. It is also here that we find nearly all of the Paleozoic shallow-water hold-overs in the succeeding period, the Triassic.

The cooled but not frigid climate that followed the magnificent mountain-making at the close of the Cretacic also produced striking changes in the organic world. These changes were less marked than those of Permic time and more noticeable among the land animals than those of the marine waters, affecting especially the over-specialized, large, thick-shelled, and degenerate stocks.

Great changes were again produced among the large land animals of the world, as well as among those of the polar and temperate oceanic waters, by the glaciation of Pleistocene time. The present shallow waters of the equatorial region still maintain the late Tertiary faunas, and Africa is the asylum where the higher Pliocene land animals have been preserved into our time.

What the effects of the Proterozoic glacial climates were upon the living world of that time it is impossible to say, because we have as yet discovered but little of the organic record. The apparently sudden appearance of life at the base of the Cambric is partially explained by the widespread absence of the marine Proterozoic record, an era during which the nuclear portions of the continents appear to have been decidedly emergent for a very long time.

The marine "life thermometer" indicates vast stretches of time of mild to warm and equable temperatures, with but slight zonal differences between the equator and the poles. The great bulk of marine fossils are those of the shallow seas, and the evolutionary changes recorded in these "medals of creation" are slight throughout eternities of time that are punctuated by short but decisive periods of cooled waters and great mortality, followed by quick evolution, and the rise of new stocks. The times of less warmth are the *miotherm* and those of greater heat the *pliotherm* periods of Ramsay (1910: 15).

On the land the story of the climatic changes is different, but in general the equability of the temperature simulates that of the oceanic areas. In other words, the lands also had long-enduring times of mild to warm climates. Into the problem of land climates, however, enter other factors that are absent in the oceanic regions, and these have great influence upon the climates of the continents. Most important of these is the periodic warm-water inundation of the continents by the oceans, causing insular climates that are milder and moister. With the vanishing of the floods somewhat cooler and certainly drier climates are produced. The effects of these periodic floods must not be underestimated, for the North American continent was variably submerged at least seventeen times, and over an area of from 154,000 to 4,000,000 square miles (Schuchert, 1910: 601).

When to these factors is added the effect upon the climate caused by the periodic rising of mountain chains, it is at once apparent that the lands must have had constantly varying climates. In general the temperature fluctuations seem to have been slight, but geographically the climates varied between mild to warm pluvial, and mild to cool arid. The arid factor has been of the greatest import to the organic world of the lands. Further, when to all of these causes is added the fact that during emergent periods the formerly isolated lands were connected by land bridges, permitting intermigration of the land floras and faunas, with the introduction of their parasites and parasitic diseases,* we learn that while the climatic environment is of fundamental importance it is not the only cause for the more rapid evolution of terrestrial life. Unfortunately, the record of land life,

* This subject is fully discussed by R. T. Eccles, M.D., in the following papers: "Parasitism and Natural Selection," "Importance of Disease in Plant and Animal Evolution," "The Scope of Disease," and "Disease and Genetics." Medical Record for July 31, 1909; March 16, 1912; March 8, and August 2, 1913.

and especially of the animal world, is the most imperfect of all paleontologic records until we come to Tertiary time. The known mammal history is a vast one and, although very difficult to interpret from the climatic standpoint, we have in the work of Depéret (1909) and Osborn (1910) glimpses into the many temperature fluctuations, faunal isolations, and intercontinental radiations of Tertiary time. The history of the Tertiary is the last one of at least three previous and similar records (Mesozoic, later and earlier Paleozoic) of vastly longer eras, taking us back to a time when the lands were without visible life.

In conclusion, it is seemingly clear that the variability in the storage of solar radiation by the earth's atmospheric blanket and by oceanic waters, and the consequent climatic variations of the past and present are due in the main to topographic changes in the earth's crust. These telluric changes alter the configuration of the continents and oceans, the air currents (moist or dry), the oceanic currents (warm, mild, or cool), and the volcanic ash-content of the atmosphere.

On the other hand, a great deal has been written about the supply and consumption of the carbonic acid of the air as the primary cause for the storage of warmth by the atmospheric blanket. A greater supply of carbon dioxide is said to cause increase of temperature, and a marked subtraction of it will bring on a glacial climate. This aspect of the climatic problem is altogether too large and important to be entered upon here. It is permissible to state, however, that the glacial climates are irregular in their geologic appearance, are variable latitudinally, as is seen in the geographic distribution of the tillites between the poles and the equatorial region, and finally that they appear in geologic time as if suddenly introduced. These differences do not seem to the writer to be conditioned in the main by a greater or smaller amount of carbon dioxide in the atmosphere, for if this gas is so strong a controlling factor, it would seem that at least the glacial climates should not be of such quick development. On the other hand, an enormous amount of carbon dioxide was consumed in the vast limestones and coals of the Cretacic, with no glacial climate as a result; though it must be admitted that the great limestone and vaster coal accumulations of the Pennsylvanic were quickly followed by the Permic glaciation. Again it may be stated that the Pleistocene cold period was preceded in the Miocene and Pliocene by far smaller areas of known accumulations of limestone and coal than during either the Pennsylvanic or Cretacic, and yet a severe glacial climate followed.

Briefly, then, we may conclude that the markedly varying climates of the past seem to be due primarily to periodic changes in the topographic form of the earth's surface, plus variations in the amount of heat stored by the oceans. The causation for the warmer interglacial climates is the most difficult of all to explain, and it is here that factors other than those mentioned may enter.

Granting all this, there still seems to lie back of all these theories a greater question connected with the major changes in paleometeorology. This is: What is it that forces the earth's topography to change with varying intensity at irregularly rhythmic intervals? This difficult and elusive problem the older geologists solved with a great deal of assurance by saying that such change was due to a cooling earth, resulting in periodic shrinkage; but the amount of shrinkage that would necessarily have taken place to account for all the wrinklings and overthrustings of the earth's crust during geologic time would be far greater than that which has apparently occurred. Further, a cooling earth is yet to be demonstrated. Again, some paleogeographers seem to see a periodic heaping up of the oceanic waters in the equatorial region and a pulsatory flowing away later toward the poles. If these observations are not misleading, are we not forced to conclude that the earth's shape changes periodically in response to gravitative forces that alter the body-form?

SUPPLEMENTARY NOTES ON GLACIATION BEFORE THE PERMIC PERIOD.

PRE-DEVONIC GLACIAL DEPOSITS OF SOUTH AFRICA.

In Cape Colony, South Africa, there is a thick marine series of shales and sandstones known as the Bokkeveld series, which appears to be of late Lower Devonic age. In western and southern Cape Colony it is everywhere seen to lie upon the Table Mountain series of wide distribution and with evidence of a glacial climate. The actual contact of these two series of strata shows "no signs of unconformity" between them, but in the places "where a clean-cut section of the junction can be seen," as "that on the left bank of the Gamka River immediately above its great Poort through the Zwartebergen, * * * 'the end of the white sandstones [of the Table Mountain series] and the beginning of the blue-black shales of the Bokkeveld is so sudden and exact that one can place a knife between them and say confidently that on one side are the rocks of the Table Mountain series and on the other those of the Bokkeveld series' " (Rogers, 1905: 121). This sharp differentiation of the Lower Devonic black shales from the white sandstones of the Table Mountain series seems to indicate clearly that the contact is a disconformable one and that the sea invaded a land of sandstones. If this is true, the section is broken and we can not therefore positively state the age of the Table Mountain series—it has as yet yielded no fossils of stratigraphic value—other than that it is older than Devonic, but how much older is still to be determined. The facts, however, that the rocks older than the Table Mountain series are far more deformed and greatly intruded by igneous materials, that the Table Mountain and Bokkeveld series do not give evidence of a long erosion interval between them, and that both were deformed together subsequent to Bokkeveld time, seem to indicate that the age of the former is rather late Siluric than early Devonic. The further fact that the fossils are bivalves and gastropods indicates clearly that the Table Mountain series is of post-Cambric deposition.

Rogers also says:

"The Table Mountain series is remarkably constant in lithological characters throughout its extent. The maximum thickness is about 5,000 feet, and of this more than 4,000 feet are sandstones or quartzites" (107).

"The whitish-grey colour of so much of the sandstone belonging to this series is due to weathering. At a distance of 1 or 2 feet from the outside the rock is usually blue, owing to a small quantity of iron in the state of ferrous compounds" (108).

"A very frequent characteristic of the sandstones of this group is the occurrence of round pebbles of white quartz up to 3 inches in diameter. They usually occur singly, more rarely in thin layers a few feet long and about an inch thick. The pebbles themselves are rarely more than an inch in diameter. It is rather difficult to explain the frequence of isolated pebbles in the sandstone without recourse to some agency that lifted pebbles from the shore and dropped them in deeper waters" (109–10).

"In the western mountains a second shale band is found about 1,000 feet below the top of the series. * * * The most interesting point about the Pakhuis section is the occurrence of pebbles up to 5 inches in diameter scattered irregularly through the shale and mudstone, without any tendency to form beds of conglomerate. Several of the pebbles have been found to be flattened on one or more sides and deeply striated in the manner characteristic of pebbles that have come from a glaciated region" (111–12).

"The occurrence of flattened and striated pebbles scattered at intervals through a fine-grained laminated rock is very strong evidence that glacial conditions prevailed on the land whence the pebbles came, and that these pebbles were carried away from the land by floating ice and dropped by the melting of the ice on to the mud being deposited at the bottom of the water" (113).

"If the Table Mountain sandstone is regarded as an ordinary coarse deposit formed in either a fresh-water basin or the sea, the land from which the material was washed can not have lain far from the present outcrops of the rock. The only evidence of the closer proximity to land of one part of the sandstone than another is the greater development of conglomerates on the west, in the Piquetberg Division and the Olifant's River Mountains, than elsewhere. There is no such evidence known from the Bokkeveld Mountain, or along the Zwartebergen, or the south coast. At present, then, we must conclude that while the nature of the rock renders it probable that the Table Mountain series, so far as exposed in the Colony, was formed not far from land, and that consequently the land lay more or less parallel to the present distribution of the series, the only definite clue to the position of any part of that land is to be found in the conglomerates of the west" (116–17).

Hatch and Corstorphine state:

"Fossils are practically unknown, but Griesbach found some small bivalves and a finely striated *Patella*, both too indistinct for determination, in certain shales, which he considered interbedded in the series at Kranz Kop, near Greytown. Anderson, who visited the locality, during the period covered by his first report, was unsuccessful in his search for additional organic remains" (1909: 77–8).

From an earlier paper by Rogers and Schwarz the following is gleaned:

"Not only is the rock similar to some varieties of the Dwyka conglomerate in general lithological character, and in being what we may call a conglomeratic mudstone, but glaciated pebbles occur in it. * * * The pebbles scattered at intervals through the conglomeratic mudstone are of all sizes up to 5 inches in length. They consist of quartz, quartzite, grits, slaty rocks, granite, and felsite. The small, whitish, often nearly spherical quartz pebbles found in this rock are also very characteristic of the sandstone above and below, in which they occur isolated and in thin beds of conglomerate. We picked out nine pebbles from 1½ to 4 inches in length, which have the characteristic form of glaciated stones, that is, they are flattened on one or more sides, and the flat faces show scratches, often arranged in parallel groups, but the other parts of the surface are also sometimes striated. * * * This evidence, then, irresistibly forces us to the conclusion that in South Africa during the time of the deposition of the Table Mountain sandstone—that is, in about lower Devonian times—glacial conditions existed somewhere in this neighbourhood. We had no opportunity of examining the shale-band north of this, but to the south, ice-scratched boulders do not occur in it, so that presumably the boulders came from the north, just as the Dwyka boulders did" (1901: 78–9).

LATEST PROTEROZOIC GLACIATION.

Australia.—Below the great tillite zone there are over 11,000 feet (in 1912 Howchin states 40,000 to 50,000, including the Cambric) of conglomerates, grits, thick feldspathic quartzites, slates and phyllites, and thin and thick zones of limestone resting upon an ancient complex of highly deformed and altered rocks. On these strata rests the great zone of tillite, attaining thicknesses ranging from 592 to about 1,500 feet. Throughout this mass of material no recognizable fossils are as yet known and therefore its age cannot be determined other than that it is older than the overlying Lower Cambric strata.

Upon these older coarse strata rests "conformably" the Lower Cambric series, the lithological features of which "are in strong contrast" to the older series above described. The basal Cambric beds are known as the Tapley's Hill slates, with a thickness of over 2,000 feet. These pass upward into calcareous slates and finally into "a very pure limestone, oolitic in structure, bluish in its lower portions and reddish in the upper," known as the Brighton limestone. It is here that the Lower Cambric Archæocyathinæ make their appearance. Still higher appear purple slates, then quartzites and purple limestones, together some hundreds of feet thick. It is at the top of this series that comes in the great Archæocyathus coral reef and other Cambric fossils, now more or less transformed into marble beds fully 200 feet thick. The two fossiliferous horizons are separated from one another by about 1,000 feet of strata. All of the Cambric and lower strata are now deformed into mountain ranges.

Howchin says further:

"The beds which give evidence of glacial origin may be described as consisting mainly of a groundmass of unstratified, indurated mudstone, more or less gritty, and carrying angular, subangular, and rounded boulders (up to 11 feet in diameter), which are distributed confusedly through the mass. It is, in every respect, a characteristic till. The included stones sometimes occur in pockets or groups, but the rock never becomes a typical conglomerate. Coarse angular grits and quartzites often occur in the form of irregular deposits, mixed with the finer groundmass, and these may or may not carry boulders. * * *

"In most sections there are more or less regularly-stratified beds or bands, which occur at various horizons in the till. These may be of quartzite, finely-laminated slate, or limestone. The last-named seldom exceed 2 or 3 feet in thickness, are often gritty, and contain angular stones. * * *

"The occurrence of isolated and irregularly-distributed boulders is a constant feature in the exposures of the gritty mudstone, or till; but these stones vary in size, relative numbers, and to some extent in their petrological types, in different localities. A close-grained and very siliceous quartzite usually supplies the commonest variety. * * *

"Although the general features of the beds supplied a strong *prima-facie* probability that they represented an ancient till, their glacial origin was not affirmed until the discovery of ice-scratched boulders placed the question beyond doubt. This culminating evidence was obtained, in the first instance, at Petersburg (on the Northern Railway from Adelaide) in 1901, and was subsequently confirmed during a visit to the same place by Professor T. W. E. David, F.R.S., Mr. E. F. Pittman, the Government Geologist of New South Wales, and myself. In association with those two experienced geologists, fifteen glaciated stones were obtained during a search of two hours.

"The erratics are frequently facetted, as well as striated, under ice-action. The striæ vary in depth and direction on the same face, and are often as distinct and fresh-looking as those which occur on the stones of the Pleistocene Boulder-Clay" (1908: 239–41). [The area of tillite accumulation] "was probably bounded on the south and west by moderate highlands, consisting of pre-Cambrian (Algonkian) quartzites, schists, limestones, and other sediments with exposed igneous batholiths and dikes of varied types. The pre-Cambrian complex had been subjected to great waste and was probably in the form of subdued relief at the time of the Cambrian glaciation. Remnants of this pre-Cambrian continent are found in the geological axes of the Mount Lofty ranges, Yorke Peninsula, and Kangaroo Island; the crystalline ranges of Eyre Peninsula, the porphyrite outcrops of the Gawler ranges, and the igneous and metamorphic plateau of Western Australia.

"In no instance has a glaciated floor been observed, the occurrence of which would suggest the probability of ice-action above sea-level. The absence of such an ice-marked floor, over the area in question, is not, however, to be wondered at when in no case have the glacial deposits been discovered in contact with a pre-Cambrian surface. The Cambrian till is found resting conformably on laminated quartzites in an orderly succession, and while the junction between the respective beds is always sharp and decided, it seems moderately certain that the glacial débris was laid down on a floor of contemporary marine deposits—in which case the agent of distribution must have been floating ice. This view is supported by the fact that the glacial material forms, practically, one continuous sheet, spread over an immense extent of country, and maintains a remarkable uniformity as to thickness, lithological characteristics, and types of erratics throughout its entire extent. At the same time it is very probable that the ice-field was at no great distance from this area of deposit" (1912: 197–8).

The following will make it clear that in all probability there is a great time hiatus without mountain-making movements between the Lower Cambric and the tillite.

In the Onkaparinga Valley, about 20 miles south of Adelaide, a Lower Cambric impure limestone *rests sharply and without transition* on a series of tillite beds here 570 feet thick, separated by two thin quartzite zones together having a thickness of 22 feet.

In the Sturt Valley section, a few miles south of Adelaide, may also be seen the contact between the Lower Cambric and the tillite. Here also the basal Cambric bed is an impure dolomitic limestone 4 feet thick, which *without transition* rests "immediately upon characteristic till" (1908: 251), here nearly 800 feet thick.

In the Appila-Gorge section the tillite upper boundary "is marked by a sharp line of division, in which boulder-clay with big erratics is covered by a homogeneous fissile slate or shale" (253). The tillite is here about 1,526 feet thick, divided into three divisions: "(*a*) An upper till of 120 feet; (*b*) an interbedded series of slates to 656 feet; and (*c*) a lower till of 750 feet" (253).

In Norway, according to Strahan,

"The sandstones occur in the most irregular manner and wedge in so suddenly as almost to resemble included masses; they contain also fragments of shale more or less rolled, and in this and other respects indicate that deposition alternated with erosion under the influence of variable currents. * * * The Gaisa beds present only such features as are common to rocks of the type of the Wealden, Trias, Coal Measures, or Old Red Sandstone, and give no hint of the action of ice. But on visiting the section near Bigganjargga, referred to by Dr. Reusch, I found a deposit of which I have seen no counterpart in any of those formations. * * * In the lowest ledge, just above high-tide mark, a lenticular mass of darker rock [a tillite] intercalated between the ledges of sandstone at once arrests the attention, even as seen from the deck of a steamer.

"The mass itself is a boulder-rock quite unlike any of the Gaisa sandstones or conglomerates which I saw elsewhere. It is referred to by Dr. Reusch as a conglomerate, but from the fact of its being neither stratified nor waterworn I prefer to avoid the use of that term. It may be described as a dark-bluish or ashy-grey friable rock, composed of a heterogeneous mixture of grit, sand, and clay of all degrees of coarseness, and containing boulders ranging up to 2 feet in length scattered through it. Though quite unstratified, it shows here and there a slight schistose structure. The included boulders, which are of all shapes and lie at all angles, consist principally of red and grey granites, and of quartz-grits resembling those of the Gaisa formation. I did not succeed in finding any striated blocks, but the fact that the matrix has been hardened and adheres closely to the boulders prevented me from examining more than two or three in the limited time at my disposal. From a similar boulder-rock at Mortensnes, however, which I unfortunately missed seeing, Dr. Reusch describes and figures well-glaciated blocks of dolomite. * * * The form of the intercalated mass of boulder-rock, as well as the fact that fragments of it occur in the base of the overlying strata, indicate that it underwent denudation before it was buried.

"The boulder-rock rests on a regularly-bedded sandstone of the usual type, and has been weathered back so as to expose several square yards of the remarkably even surface of that rock. The platform thus exposed is not only smoothed, but conspicuously and characteristically striated. The scratches can be followed in some cases for 2 or 3 yards, not only up to the foot of the little cliff of boulder-rock, but under it, a fact of which I made certain by wedging out some masses of that material and exposing a fresh portion of the platform. * * * The sandstone is traversed by a few irregular joints, the lines due to which, however, on the striated platform bear no resemblance to glacial groovings. The striæ have, beyond question, been cut into that surface independently of any structure possessed by the rock, and are in all respects characteristic glacial markings.

"The evidence detailed above seems to leave no room for doubt that we have here an intercalation of a true glacial till in the Gaisa formation. * * * I accept without hesitation Dr. Reusch's conclusion that the phenomena are due to glacial action, and that they were produced contemporaneously in the Gaisa formation" (1897: 140–43).

"The Gaisa beds, so far as I saw them, do not suggest the immediate neighbourhood of a mountain-region, for such conglomerates as they contain are neither coarse nor plentiful. The facts tend rather to indicate a temporary deterioration of climate" (145).

UNDATED PROTEROZOIC GLACIATION OF CHINA.

Nan-t'ou formation.—A series of sandy and argillaceous rocks seen only beneath the Cambric limestone cliffs at Nan-t'ou (long. 110° E., lat. 31° N.). The basal strata, Blackwelder states, "consist of arkose sandstone and conglomerate, which are purplish-brown in color below, but gradually become white and purely quartzose in the upper strata. Throughout the total thickness of perhaps 150 feet, 45 meters, the texture is coarse and gritty" (1907: 267).

He says further:

"The upper member of the formation is distinct from the sandstone, but we did not see the contact and do not know the exact relations.

"The next outcrops above the sandstone occur 100 feet, 30 meters, up the slope, and expose about 120 feet, 35 meters, of hard massive boulder-clay or tillite, which is neither fissile nor stratified. It is a greenish gritty clay-rock of hackly fracture, in which lie irregular stones of various sizes and kinds, with their long axes at random angles with the horizontal. * * * The rocks range in size from sand-grains to blocks 50 to 75 cm. in length, and there is no suggestion of the assortment of the individual sizes. Coarse and fine particles lie indiscriminately mingled and chaotic in their arrangement. The forms of the majority of the stones are subangular, *i. e.*, angles are present, but are smooth and rounded. The flattish surfaces of such slowly weathering rocks as the massive siliceous ferruginous limestone are polished and scratched in various directions, and are identical in aspect with pebbles from the Pleistocene boulder-clays of North America and Europe. The scratched stones were found in numbers firmly fixed in the green tillite, in such a condition as to show that they had never been disturbed nor subjected to surface abrasion since they were imbedded there in early Paleozoic time.

"The promiscuous arrangement of the pebbles, the heterogeneity of the mass and of its lithologic components, the subangular shapes of the stones and especially their striated surfaces are positive characteristics of glacial till. The evidence of glacial origin is quite as plain as that usually seen in the Pleistocene of the United States or Great Britain. * * * It is highly probable that these glacial beds on the Yang-tzi are of early Cambrian age" (267–9).

To this Willis adds:

"*Nan-t'ou tillite.*—The Nan-t'ou glacial deposit occurs in longitude 111° east, latitude 31° north, about 200 feet, 60 meters, above sea. It evidently accumulated close to sea-level in early Sinian [= Cambric] time, as it is overlain by marine limestones of that age. At the base the plane of the pre-Sinian unconformity is characteristically developed and covered by a cross-bedded quartzite, which may have been either river deposit or beach. The top of the quartzite is generally covered in the type locality and a cultivated slope interrupts the section for 100 feet, 30 meters. Above the terraced fields occur steep banks of tillite, a greenish rock, about as hard as unweathered shale, of irregular hackly fracture, not stratified, and containing pebbles and boulders of various kinds and sizes, many of which are striated. The thickness seen is 120 feet, 36 meters.

"At the top of the tillite, beneath a cliff, is a well-exposed contact with the overlying limestone. The tillite passes into a greenish shale, consisting of the same materials, including characteristic pebbles, all rearranged by the water. This shale conglomerate is about 2 feet thick and grades into the overlying limestone, the basal layer of a great thickness of Sinian.

"The facts clearly demonstrate the presence at this spot of a glacier which gave way to marine waters and left a deposit of till that was slightly washed by waves before it was buried beneath calcareous mud. * * *

"Whether the Nan-t'ou glacier was an exceptional occurrence or a representative of an extensive system, only in degree affects the deduction that the temperature of early Sinian time was low. Glaciation in latitude 31° near sea-level presents, it is true, a problem which refrigeration alone will not solve, especially as no traces of contemporaneous glaciers have been found farther north; but there can be no doubt that it signifies severe cold throughout northern Asia" (1909: 39–40).

Professor J. P. Iddings, while on a geologic tour in China, visited the Nan-t'ou region in October 1909, and from him has been received the following description of the tillites:

"The tillite is extensive and quite persistent in character, though somewhat variable in thickness. It is interbedded with the basal sandstone resting on the granite-gneiss, and I did not find it in contact with the granite. I first examined the locality discovered by Willis and Blackwelder. * * * The formation extends for 3 or 4 miles back from the Yangtsze to the north along the base of the cliff of limestone. Some distance back from the river, I crossed the branch creek that enters the Yangtsze at Nantou. The branch is in granite which rises in the east slope about 400 feet. Here occurs the base of the conglomeratic red sandstone, dipping 5° SE., strike N. 40° E. (magnetic). The top of the sandstone is 200 feet higher. The upper 50 feet contain white layers, alternating with red. Near the base of the tillite there are some thin clay layers in the sandstone, and in the base of the tillite is some red sandy rock. The two appear to mix and to grade into one another. Similar mixture and gradation were observed in numerous places farther north. The tillite at the location on the branch creek is green and of the same aspect as in other places visited. It contains many boulders and pebbles in the middle portion; not so many in the basal or in the uppermost portions. There were no signs of bedding, and no intercalated stratum of sandstone, as in a case south of Huang-Ling-Miao noted later. The tillite is about 150 feet thick and is overlain by limestone, the bottom layer of which is more massive than the higher layers.

"Traveling northward across spurs that set forth from the cliffs east of a branch stream, the base of the sedimentary rocks rises gradually as far as I went, about 3.5 miles in a direct line from Yangtsze River. I observed a fault cutting across the spurs shifting the exposures of tillite, the trend of the fault being about with the strike (about N. 45° E.), and the hade very steep, about 75°, apparently to the west, though not distinct. The strata and the granite on the west were raised with respect to the same on the east, the displacement being about 100 feet. The result is apparent variableness in the thickness of the tillite bed, and to cause it in places to abut against the granite.

"Crossing to south side of Yangtsze opposite Nantou, I followed the base of the stratified rocks westward as they rose above the granite, and occasionally saw exposures of tillite. Back of Huang-Ling-Miao, granite extends up spurs to 1,700 feet above the river; then follow about 300 feet of massive strata of red sandstone, which is immediately overlain by tillite, the lower 5 feet of tillite having a layer of sandstone blended with it. There are few boulders in the lowest part, but more higher up. The pebbles are of granite, gneiss, porphyry, slate, limestone, flint, and quartz. The lower portion of tillite is yellow and clayey, the upper portion is green and indurated, as at Tungling. About 200 feet from the base is a massive stratum of red sandstone, about 6 feet thick, having the same strike and dip as the strata above and below it. Above this there is tillite for 200 feet more, making the thickness of the tillite in this locality between 400 and 500 feet. The overlying limestone is somewhat brecciated at its base for 6 inches to a foot, and then becomes massive, with some contortions of the lines of bedding, for a thickness of 3 or 4 feet. Then follows thinly bedded to fissile arenaceous limestone, and layers of arenaceous shales quite uniform in character up to about 2,700 feet above the river. The strike of the strata is N. 45° E., dip 10° SE. No trace of fossils was seen, though there were fine exposures of strata and talus. The cliffs rise to about 3,500 feet above the river. The area of granite hills north of Yangtsze River was well seen from a high spur south of the river. The sedimentary strata were seen to arch in a dome around flanks of the granite hills to west and north and to east and north. South of the river sedimentary strata appear to extend in an arch around to Tungling, at the lower entrance to Lukan gorge on the west side of the granite arch.

"At Tungling the tillite is seen on both sides of Yangtsze River, near the shores. On the north side, in a bluff near the landing, it is about 300 feet thick. The tillite here overlies red basal sandstone, but the contact is not exposed. The tillite is overlain by a massive stratum of limestone and of fissile layers, and then by thicker strata of limestone. No fossils were found in the limestone or in the talus at the base of the cliffs to the west of Tungling.

"On the south side of the river, opposite Tungling, tillite is well exposed on the beach near the water beneath limestone, with strike N. and S., and a dip 25° W. The tillite is well indurated, and carries fewer boulders in its upper than in its lower portion. The erratics embrace granite, gneiss, quartz-porphyry, slate, limestone, and quartz. The tillite is here about 250 feet thick, and rests on red sandstone, the contact with which is seen for a short distance only. The underlying sandstone, about 100 feet thick, becomes more pebbly and conglomeratic toward its base, and is arkose near its bottom. It rests on decomposed hornblende-schist, no granite being seen here on the south side of the river. On the north side there is decomposed granite beneath the sandstone, and farther off there is hornblende-schist.

"From these observations it appears as though the tillite extended continuously from where it is seen beneath the limestone east of Nantou, around the south flank of the granite-gneiss area, to and beneath the limestone cliff west of Tungling, and that it extends northward from Nantou at least some distance. It appears to be thickest south of Huang-Ling-Miao and thinnest in its extension toward the northeast.

"I spent parts of five days in five different places hunting for fossils without seeing one, so they must be scarce. The rocks appear to be free from trace of them for some hundreds of feet in thickness, as I examined carefully the talus below several high cliffs. I was disappointed not to find any."

From the fact that no one has yet found fossils in the very thick and well-exposed dolomites that overlie the tillites in the immediate area of the glacial deposits, the question may well be asked: How do we know that the dolomites at their base are of Middle Cambric age? In order to answer this question, the writer corresponded with Blackwelder on the subject, receiving the following reply under date of March 24, 1913.

"In the Yangtze region there are two very thick massive limestone formations, neither of them rich in fossils, but both with their own distinctive lithologic characters. These are separated by an easily recognized body of green shale. In crossing the mountains north of the Yangtze River, and in following down the great gorges of the latter, these formations were repeated again and again in great open anticlines and synclines, interrupted by only occasional faults. The age of the lower massive limestone was approximately fixed by the finding of a rich Mohawkian fauna near the top of it, perhaps 50 miles north of the Yangtze River.

"The Middle Cambrian fossils which were found several days' journey northwest of the tillite exposure, came from rocks very highly folded and faulted, so that their stratigraphic relations are uncertain. Lithologically, however, the beds were much like those just below the great cliff limestone at Nan-t'ou, in that they contained many layers of gray and black oolite. I think it highly probable that the horizon of the Middle Cambrian fossils is not more than a few hundred feet above the tillite and is beneath the great cliff limestone."

On the ground that none of the Lower Cambric faunas indicate cool or cold waters and in view of the further fact that in many widely separated places there are reef-making corals (Archæocyathinæ), the writer does not regard the Yangtze tillites as of Cambric age. He would, rather, refer them to the Proterozoic, but whether they are late or early in this era remains to be determined on the basis of the age of the superposed dolomites.

EARLIEST PROTEROZOIC GLACIATION OF CANADA.

Coleman says:

"For several years it has seemed to me very probable that there was a still more ancient ice age, at the beginning of the Lower Huronian in the Archean as defined in Canada, or the Archeozoic or lowest Algonkian, as defined by various American geologists. The so-called Huronian 'slate conglomerate' of Ontario has attracted attention ever since Logan and Murray mapped and described it in the typical region north of Lake Huron, nearly fifty years ago. Good descriptions of it are given by Logan in the 1863 report of the Canadian Geological Survey; where he refers to the different kinds of rock enclosed as pebbles or bowlders, granite, felsite, certain greenstones and jasper, for example; and describes the matrix as sometimes slaty, sometimes more quartzitic or like diorite or greenstone. At present the matrix would generally be called graywacke or slate, though sometimes it is schistose or looks like an eruptive rock.

"The pebbles or bowlders are in many cases subangular or sharply angular and are found miles away from any known source; and as they may be of any size up to blocks weighing tons, and are frequently very sparsely scattered through an unstratified matrix, a stone or two in several yards, one can not help suspecting that the transporting agency was ice rather than water. There are parts of the formation where the pebbles or stones are well rounded and crowded in certain bands. In such cases they are probably true water-formed conglomerates; but the prevalent type of the rock with scattered subangular stones or bowlders should not be called a conglomerate, any more than a Pleistocene bowlder clay would receive that name. The appearance of these so-called slate or graywacke conglomerates is closely like that of the Dwyka bowlder clays, for which Penck suggests the term 'tillite'; * * * rocks of the kind are found from point to point across all northern Ontario, a distance of nearly 800 miles, and from the north shore of Lake Huron in latitude 46° to Lake Nipigon in latitude 50°.

"The more schistose of these conglomerates have their pebbles flattened and rolled out into lenses not at all suggesting glacial action; but the fact that all of them, whether schistose or unmodified, occupy, so far as known, the same position, immediately over the Keewatin, and contain pebbles and bowlders of the same rocks, granite, banded jasper, etc., makes it very probable that they belong to the same age and have had a similar origin. * * *

"By the exercise of care and patience it has been possible to break from their matrix wholly or partially about twenty of these stones, mostly only an inch or two in diameter, but half a dozen from 3 to 6 inches across. As coarse-grained rocks like granite seldom show distinct striations in modern bowlder clays, felsites and fine-grained greenstones were selected to work upon. Of the twenty stones four or five are more or less striated, but only one is heavily and decisively scored. Unfortunately the matrix could not be completely removed from this one, but the exposed surfaces show the striations well on one face and distinctly on two others.

"Several of the smaller pebbles have the peculiar somewhat uneven but well-polished faces with rougher corners so often seen in the smaller stones of bowlder clay.

"Though the number of stones available is small, the proportion showing more or less striation is as large as in recent bowlder clay and all the usual features of ice-carved stones are found in them. It may be added that they were taken from undisturbed parts of the formation with no faulting to cause slickensides, and that the stones themselves had not been squeezed nor broken in the matrix.

"No striated surfaces were found where the conglomerate rested on the underlying Keewatin; but the only contact of the two rocks examined was unfavorable for displaying such a surface. [Such are now known in three places and were described in 1912.] Mining operations show that the rocks beneath the Huronian have on the whole an uneven, somewhat undulating surface of low hills and valleys, the conglomerate often more or less filling in these valleys. * * *

"The evidence for a Lower Huronian Ice Age may be summed up as follows:

"A peculiar rock consisting of graywacke or finer materials showing little or no stratification but containing pebbles or stones, sometimes crowded, but more often scattered a few feet apart, is found from point to point over an area 800 miles long by 250 miles broad. The stones are of all sizes up to diameters of several feet and of all shapes from rounded to angular, many being subangular with rounded corners. The stones are of several different kinds, some fragments of the immediately underlying rock, others having a distant source.

"In the Cobalt mining region a few polished and striated stones have been broken out of the matrix. They are closely like stones from the Pleistocene bowlder clay of the same region except that they lack the Niagara limestones of the recent drift.

"Hand specimens of matrix and enclosed pebbles are precisely like the Dwyka tillite or conglomerate of South Africa, which is undoubtedly of glacial origin.

"Against the glacial theory is the fact that no *roches moutonnées* have yet been found on the underlying Keewatin rocks. All the positive evidence is favorable to the theory of glacial action as the cause of these curious bowlder-strewn rocks.

"If the evidence given above is accepted, the occurrence of glaciation is probable over an area too large to be the work of merely local mountain glaciers, and one must assume the presence of ice-sheets comparable to those which formed the Dwyka.

"The Lower Huronian is the second formation in the geological succession in North America, only the Keewatin coming before it; so that the probable action of ice on a large scale is pushed back almost to the beginning of known geological time. This implies that the climates of the earlier parts of the world's history were no warmer than those of later times, and that in Lower Huronian times the earth's interior heat was not sufficient to prevent the formation of a great ice-sheet in latitude 46°" (1907: 188–92).

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PART III.

STATISTICS.

TABLE A.—*Average Growth of 451 Sequoia Trees in California, by Decades and Centuries of the Life of the Trees, beginning with their Youth.*

[This table is the basis of the Corrective Factor for Age, shown in figures 35 and 36, and first column of Table E.]

Age of trees in years.	* No. of measurements.	Average growth.	Age of trees in years.	* No. of measurements.	Average growth.	Age of trees in years.	* No. of measurements.	Average growth.	Age of trees in years.	* No. of measurements.	Average growth.	Age of trees in years.	* No. of measurements.	Average growth.
		mm.			*mm.*			*mm.*			*mm.*			*mm.*
1–10	635	27.50	111–120	777	21.81	221–230	777	21.20	1051–1150	5,752	8.70	2151–2250	689	7.55
11–20	644	26.16	121–130	780	21.96	231–240	777	20.91	1151–1250	5,314	8.38	2251–2350	514	7.37
21–30	657	23.87	131–140	781	22.08	241–250	777	20.40	1251–1350	4,569	8.10	2351–2450	280	7.63
31–40	666	22.23	141–150	781	22.10	251–350	7,779	20.11	1351–1450	3,992	8.08	2451–2550	110	6.91
41–50	676	21.52	151–160	781	22.31	351–450	7,700	15.41	1451–1550	3,503	7.87	2551–2650	110	6.95
51–60	684	21.27	161–170	783	22.10	451–550	7,485	12.13	1551–1650	2,991	7.60	2651–2750	110	7.50
61–70	687	21.05	171–180	783	22.08	551–650	6,922	11.90	1651–1750	2,521	7.48	2751–2850	60	6.84
71–80	690	21.05	181–190	783	21.91	651–750	6,911	10.32	1751–1850	2,186	7.62	2851–2950	40	6.38
81–90	695	21.03	191–200	783	21.91	751–850	6,605	9.88	1851–1950	1,721	7.95	2951–3050	30	5.43
91–100	772	21.60	201–210	784	21.89	851–950	6,426	9.44	1951–2050	1,424	7.89	3051–3150	20	5.60
101–110	777	21.72	211–220	784	21.28	951–1050	6,168	9.02	2051–2150	1,196	8.03	3151–3250	18	6.70

* This means the total number of groups of rings upon which the figures are based. Each group contains 10 rings.

TABLE B.—*Comparative Growth of Short-lived and Long-lived Sequoias, by Groups; Corrective Factor for Longevity.* (See figure 37.)

Group.	First 250 years of life.			250 to 650 years of age.			650–1050 years of age.			1050–1450 years of age.			1450–1850 years of age.			0–1050 years of age.			Value of smoothed curve based on preceding column.	Corrective factor for longevity, based on preceding column.
	* Basis in decades.	* Total growth.	Average growth.	Basis in decades.	Total growth.	Average growth.	Basis in decades.	Total growth.	Average growth.	Basis in decades.	Total growth.	Average growth.	Basis in decades.	Total growth.	Average growth.	Basis in decades.	Total growth.	Average growth.		
1	173	3,583	20.72																15.70	1.00
2	198	3,485	17.61																15.70	1.00
3	351	8,195	22.33																15.70	1.00
4	1,654	42,379	25.60																15.70	1.00
5	541	12,278	22.69	834	13,782	16.51													15.70	1.00
6	257	6,478	25.21	400	5,991	14.77													15.70	1.00
7	433	10,227	23.43	680	10,314	15.21													15.70	1.00
8	706	15,507	21.97	1,040	15,954	15.31													15.70	1.00
9	1,024	22,076	21.55	1,680	27,220	16.20	1,664	18,781	11.31							4,384	68,077	15.52	15.65	1.002
10	1,059	26,015	24.60	1,680	25,881	15.42	1,680	18,021	10.72							4,119	62,917	15.80	15.60	1.005
11	1,899	40,331	21.23	3,000	48,405	16.11	3,000	33,882	11.30							7,899	122,618	15.55	15.40	1.02
12	1,410	35,744	25.36	2,360	38,466	16.30	2,360	26,786	11.32							6,130	100,976	16.35	15.15	1.035
13	1,237	26,406	21.32	1,960	28,580	14.57	1,960	18,457	9.40	1,948	17,008	8.73				5,157	73,443	14.21	14.90	1.05
14	1,237	26,176	21.16	2,040	30,964	15.16	2,040	21,335	10.45	2,040	19,116	9.87				5,317	78,475	14.73	14.60	1.075
15	1,187	24,040	20.28	1,880	24,459	13.01	1,880	16,733	8.90	1,880	15,441	8.23				4,947	65,232	13.21	14.30	1.095
16	755	14,489	19.20	1,320	18,054	13.67	1,320	12,179	9.22	1,320	10,468	7.93				3,395	44,722	13.18	14.00	1.12
17	1,133	26,303	22.35	1,880	25,905	13.78	1,880	15,479	8.23	1,880	13,427	7.15	1,866	12,692	6.80	4,893	67,687	13.82	13.75	1.14
18	707	14,159	20.05	1,200	16,317	13.61	1,200	10,220	8.52	1,200	8,936	7.44	1,200	9,389	7.82	3,107	40,696	13.09	13.50	1.16
19	649	12,142	18.75	1,000	15,087	15.09	1,000	8,300	8.30	1,000	8,221	8.22	1,000	8,396	8.40	2,649	35,529	13.40	13.25	1.185
20	1,223	21,039	17.22	1,960	29,432	15.01	1,960	17,566	8.97	1,960	15,337	7.84	1,960	15,288	7.80	5,143	68,037	13.24	13.00	1.205
21	376	7,200	19.15	680	10,041	14.78	680	5,518	7.63	680	4,880	7.18	680	5,072	7.47	1,736	22,759	13.10	12.75	1.23
22	587	11,030	23.92	960	12,475	12.98	960	8,077	8.42	960	6,451	6.72	960	6,925	7.22	2,507	34,582	13.77	12.50	1.255
23–25	355	5,899	16.61	680	9,069	13.36	680	5,364	7.89	680	4,300	6.33	680	4,835	7.12	1,715	20,332	11.83	†23 12.30	1.275
26–31	271	4,564	16.86	440	6,066	13.80	440	3,207	7.30	440	2,997	6.78	440	2,631	5.98	1,151	13,837	12.02	24 12.15	1.29
																			25 12.00	1.31
																			26 11.90	1.32
1–4	2,376	57,642	24.28																27 11.90	1.32
5–8	1,937	44,490	22.98	2,954	46,041	15.62													28 11.90	1.32
9–12	5,392	124,166	23.08	8,720	139,972	16.05													29 11.90	1.32
13–16	4,416	91,111	20.63	7,200	102,057	14.25													30 11.90	1.32
17–20	3,762	73,643	19.58	6,040	86,741	14.37													31 11.90	1.32
21–31	1,589	31,693	20.03	2,760	37,651	13.65														

* The first column shows the total number of decades for all the trees of a group combined, and the second column shows the total growth. That is, if 24 decades are available for one tree, the inner decade being rotted away, 23 for another, and 25 for a third, the basis would be 72.

† Numbers of later groups, which here are separated instead of being combined as in earlier columns.

TABLE C.—*List of Individual Sequoia Trees measured in California in 1911 and 1912.*

No.	Group.	Place. (See note at end of table, p. 307.)	First year* of tree.	Year* of cutting.	Age of tree at cutting.	Last decade measured.	No. of readings.	Difference between readings. A & B.	A & C.	A & D.	A & E.	Readings to be used. A.	B.	C.	D.	E.	Decades to be added and intervals. A. Dec.	A. Int.	B. Dec.	B. Int.	C. Dec.	C. Int.	D. Dec.	D. Int.	E. Dec.	E. Int.
1	8	Millwood........	983a	1884a	901	1871-1880	1	—	—	—	—	×	—	—	—	—	1	450	—	—	—	—	—	—	—	—
2	18	Do	60b	1884	1944	1871-1880	1	—	—	—	—	×	—	—	—	—	3	500	—	—	—	—	—	—	—	—
3	12	Do	560a	1884	1324	1871-1880	2	9	—	—	—	×	×	—	—	—	0	—	0	—	—	—	—	—	—	—
4	12	Do	531a	1884	1353	1871-1880	2	23	—	—	—	×	×	—	—	—	2	440	0	—	—	—	—	—	—	—
5	19	Do	129b	1884	2013	1871-1880	1	—	—	—	—	×	—	—	—	—	3	500	—	—	—	—	—	—	—	—
6	19	Do	142b	1884	2026	1871-1880	1	—	—	—	—	×	—	—	—	—	3	500	—	—	—	—	—	—	—	—
7	14	Boule.........	371a	1904	1533	1891-1900	2	16	—	—	—	×	×	—	—	—	2	510	0	—	—	—	—	—	—	—
8	10	Do..........	705a	1904	1199	1891-1900	2	1	—	—	—	×	×	—	—	—	0	—	0	—	—	—	—	—	—	—
9	4	Do..........	1304a	1904	600	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
10	5	Do..........	1287a	1904	617	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
11	4	Do..........	1313a	1904	591	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
12	1	Do..........	1618a	1904	286	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
13	13	Do	438a	1904	1466	1891-1900	3	2	18	—	—	×	×	—	—	—	0	—	0	—	—	—	—	—	—	—
14	8	Do..........	924a	1904	980	1891-1900	1	—	—	—	—	×	—	—	—	—	1	480	—	—	—	—	—	—	—	—
15	20	Do..........	285b	1904	2190	1891-1900	1	—	—	—	—	×	—	—	—	—	4	400	—	—	—	—	—	—	—	—
16	9	Converse Rob Roy.	815a	1904	1089	1891-1900	1	—	—	—	—	×	—	—	—	—	1	540	—	—	—	—	—	—	—	—
S	19	Boule..........	b	1904	....	1891-1900	....	—	—	—	—	..	—	—	—	—	—	—	—	—	—	—	—	—	—	—
18	21	Do..........	b	1904	....	1891-1900	....	—	—	—	—	..	—	—	—	—	—	—	—	—	—	—	—	—	—	—
19	4	Do..........	1318a	1904	586	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
20	3	Do..........	1412a	1904	492	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
21	7	Converse Rob Roy.	1914a	1904	890	1891-1900	1	—	—	—	—	×	—	—	—	—	1	450	—	—	—	—	—	—	—	—
22	9	Indian Basin......	885a	1903	1018	1891-1900	1	—	—	—	—	×	—	—	—	—	1	500	—	—	—	—	—	—	—	—
23	8	Do	907a	1904	997	1891-1900	1	—	—	—	—	×	—	—	—	—	1	500	—	—	—	—	—	—	—	—
24	1	Converse Rob Roy.	1646a	1906	260	1901-1910	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
25	7	Do	1015a	1904	889	1891-1900	1	—	—	—	—	×	—	—	—	—	1	450	—	—	—	—	—	—	—	—
26	4	Boule............	1363a	1906	543	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
27	9	Converse Rob Roy.	840a	1906?	1066	1861-1870	1	—	—	—	—	×	—	—	—	—	1	530	—	—	—	—	—	—	—	—
28	5	Do	1237a	1906	669	1891-1900	1	—	—	—	—	×	—	—	—	—	1	330	—	—	—	—	—	—	—	—
29	17	Do	86a	1904	1818	1891-1900	4	85	78	94	—	—	×	—	×	—	—	—	0	—	—	—	0	—	—	—
30	15	Do	247a	1906	1659	1901-1910	1	—	—	—	—	×	—	—	—	—	3	420	—	—	—	—	—	—	—	—
31	22	Converse T. S.....	473b	1906	2379	1891-1900	5	14	34	56	73	—	×	—	×	—	—	—	4	460	—	—	0	—	—	—
32	15	Converse Hoist....	225a	1906	1681	1891-1900	5	50	55	164	175	—	—	—	×	×	—	—	—	—	—	—	1	840	0	—
33	14	Converse T. S.....	388a	1906	1518	1901-1910	1	—	—	—	—	×	—	—	—	—	2	510	—	—	—	—	—	—	—	—
34	13	Converse H.......	418a	1906	1488	1901-1910	1	—	—	—	—	×	—	—	—	—	2	490	—	—	—	—	—	—	—	—
35	10	Converse T. S.....	704a	1904	1200	1891-1900	2	7	—	—	—	×	×	—	—	—	0	—	1	600	—	—	—	—	—	—
36	5	Indian Basin......	1247a	1904	657	1891-1900	1	—	—	—	—	×	—	—	—	—	1	330	—	—	—	—	—	—	—	—
37	15	Do	210a	1904	1694	1891-1900	2	14	—	—	—	×	×	—	—	—	0	—	1	850	—	—	—	—	—	—
38	5	Do	1285a	1904	619	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
39	4	Do	1359a	1904	545	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
40	19	Do	139b	1904	2043	1891-1900	4	110	121	16	—	—	×	×	—	—	—	—	1	1000	0	—	—	—	—	—
41	4	Do	1351a	1904	553	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
42	14	Do	354a	1906	1552	1901-1910	3	26	14	—	—	×	—	×	—	—	0	—	—	—	0	—	—	—	—	—
43	4	Do	1377a	1904	531	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
44	5	Do	1256a	1904	648	1891-1900	1	—	—	—	—	×	—	—	—	—	1	320	—	—	—	—	—	—	—	—
45	8	Do	935?a	1904	969	1891-1900	1	—	—	—	—	×	—	—	—	—	1	480	—	—	—	—	—	—	—	—
46	14	Do	387a	1904	1519	1891-1900	2	4	—	—	—	×	×	—	—	—	0	—	0	—	—	—	—	—	—	—
47	4	Do	1362a	1904	542	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
48	11	Do	684a	1904	1220	1891-1900	2	12	—	—	—	×	×	—	—	—	1	550	0	—	—	—	—	—	—	—
49	12	Do	513a	1904	1391	1891-1900	1	—	—	—	—	×	—	—	—	—	1	650	—	—	—	—	—	—	—	—
50	9	Do	904a	1904	1000	1891-1900	1	—	—	—	—	×	—	—	—	—	1	400	—	—	—	—	—	—	—	—
51	13	Do	417a	1904	1487	1891-1900	3	38	45	—	—	—	×	×	—	—	—	—	1	750	0	—	—	—	—	—
52	15	Do	240a	1904	1664	1891-1900	3	31	26	—	—	—	×	×	—	—	—	—	0	—	0	—	—	—	—	—
53	13	Do	411a	1904	1493	1891-1900	2	10	—	—	—	×	×	—	—	—	1	750	0	—	—	—	—	—	—	—
54	9	Do	894a	1904	1010	1891-1900	3	5	3	—	—	×	×	×	—	—	0	—	0	—	0	—	—	—	—	—
55	13	Do	436a	1904	1468	1891-1900	3	23	29	—	—	—	×	×	—	—	—	—	1	730	0	—	—	—	—	—
56	13	Do	439a	1904	1465	1891-1900	2	7	—	—	—	×	×	—	—	—	0	—	1	730	—	—	—	—	—	—
57	12	Do	538a	1904	1366	1891-1900	3	2	8	—	—	×	×	×	—	—	0	—	0	—	1	600	—	—	—	—
58	5	Do	1284a	1904	620	1891-1900	1	—	—	—	—	×	—	—	—	—	1	310	—	—	—	—	—	—	—	—
59	19	Do	121b	1904	2025	1891-1900	2	4	—	—	—	×	×	—	—	—	0	—	0	—	—	—	—	—	—	—
60	19	Do	112b	1904	2016	1891-1900	3	20	175	—	—	×	×	—	—	—	2	650	0	—	—	—	—	—	—	—
61	9	Do	868a	1904	1036	1891-1900	3	2	3	—	—	×	×	×	—	—	0	—	0	—	0	—	—	—	—	—
62	6	Do	1188a	1904	716	1891-1900	1	—	—	—	—	×	—	—	—	—	1	360	—	—	—	—	—	—	—	—
63	22	Converse Mill.....	445b	1901	2346	1891-1900	4	40	1	59	—	×	×	×	—	—	0	—	4	460	3	580	—	—	—	—
64	20	Converse H.......	238b	1891	2129	1881-1890	2	1	—	—	—	×	×	—	—	—	0	—	0	—	—	—	—	—	—	—
65	20	Do	214b	1901	2115	1891-1900	4	18	10	28	—	×	×	×	—	—	0	—	3	500	1	1050	—	—	—	—
66	20	Do	285b	1891	2176	1881-1890	2	69	—	—	—	—	×	—	—	—	—	—	0	—	—	—	—	—	—	—
67	19	Do	160b	1891	2051	1881-1890	1	—	—	—	—	×	—	—	—	—	3	500	—	—	—	—	—	—	—	—
68	21	Do	374b	1904	2278	1891-1900	3	13	14	—	—	×	×	×	—	—	2	750	0	—	0	—	—	—	—	—
69	18	Do	10b	1904	1914	1891-1900	3	19	19	—	—	—	×	×	—	—	—	—	0	—	0	—	—	—	—	—
70	20	Converse, T. S....	271b	1901	2172	1891-1900	3	75	65	—	—	—	×	×	—	—	—	—	0	—	1	1100	—	—	—	—
71	18	Converse H	26b	1904	1930	1891-1900	3	38	32	—	—	—	×	×	—	—	—	—	0	—	0	—	—	—	—	—
72	22	Do	459b	1892	2351	1881-1890	3	0	12	—	—	×	×	×	—	—	0	—	0	—	1	1170	—	—	—	—
								C & D	C & E																	
73	22	Converse, W. F....	467b	1892	2359	1881-1890	3	39	9	—	—	—	—	×	—	×	—	—	—	—	0	—	—	—	0	—
74	31	Converse H	1318b	1892	3210	1881-1890	4	68	62	38	—	—	×	—	×	—	—	—	0	—	—	—	3	800	—	—
75	2	Do	1555a	1892	340	1881-1890	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
76	20	Do	220b	1902	2122	1881-1890	3	15	128	—	—	—	—	×	—	—	—	—	—	—	0	—	—	—	—	—
77	18	Do	35b	1902	1937	1891-1900	3	14	12	—	—	×	×	×	—	—	1	900	0	—	0	—	—	—	—	—
78	10	Indian Basin.	730a	1902	1172	1891-1900	3	8	3	—	—	×	×	×	—	—	0	—	1	580	0	—	—	—	—	—
79	3	Do	1484a	1904	420	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
80	2	Do	1564a	1903	339	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
81	17	Do	22a	1903	1881	1891-1900	3	15	19	—	—	—	×	×	—	—	—	—	0	—	0	—	—	—	—	—
82	17	Do	57a	1902	1845	1891-1900	3	6	2	—	—	×	×	×	—	—	0	—	1	800	0	—	—	—	—	—
83	3	Do	1476a	1903	427	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—
84	11	Do	601a	1903	1302	1891-1900	3	6	4	—	—	×	×	×	—	—	1	650	0	—	0	—	—	—	—	—
85	11	Do	663a	1903	1240	1891-1900	3	9	3	—	—	×	×	×	—	—	0	—	1	620	0	—	—	—	—	—
86	10	Do	761a	1903	1142	1891-1900	3	16	8	—	—	×	—	×	—	—	1	560	—	—	0	—	—	—	—	—
87	3	Do	1486a	1903	417	1891-1900	1	—	—	—	—	×	—	—	—	—	0	—	—	—	—	—	—	—	—	—

* A. D. is indicated by *a*; B. C. by *b*.

No.	Group.	Place.	First year of tree.	Year of cutting.	Age of tree at cutting.	Last decade measured.	No. of readings.	Differences between readings. A & B.	A & C.	A & D.	Readings to be used. A.	B.	C.	D.	Decades to be added and intervals between them. A. Dec.	A. Int.	B. Dec.	B. Int.	C. Dec.	C. Int.	D. Dec.	D. Int.
88	2	Indian Basin....	1515*a*	1903	388	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
89	5	Do	1202*a*	1905	703	1891-1900	1	—	—	—	×	—	—	—	1	350	—	—	—	—	—	—
×	11	Eldorado........	620*a*	1864	1244	1851-1860	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
90	2	Indian Basin....	1504*a*	1903	399	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
91	12	Do	585*a*	1903	1318	1891-1900	3	6	6	—	×	×	×	—	0	—	—	—	—	—	—	—
92	17	Do	17*a*	1903	1886	1891-1900	3	4	—	—	×	×	—	—	0	—	—	—	—	—	—	—
93	3	Do	1406*a*	1903	497	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
94	3	Do	1416*a*	1903	487	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
95	2	Do	1600*a*	1903	303	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
96	15	Do	200*a*	1903	1703	1891-1900	4	17	12	41	—	×	—	×	—	—	2	550	—	—	0	—
97	16	Do	151*a*	1903	1762	1891-1900	1	—	—	—	×	—	—	—	2	600	—	—	—	—	—	—
98	21	Converse H.....	330*b*	1902	2232	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
99	14	Converse W. F...	307*a*	1902	1595	1891-1900	4	31	15	23	—	—	×	×	—	—	—	—	1	800	0	—
100	14	Do ..	309*a*	1902	1593	1891-1900	3	41	46	—	×	—	—	—	0	—	—	—	—	—	—	—
101	22	Do ..	437*b*	1902	2339	1891-1900	4	51	37	62	—	×	—	×	—	—	0	—	—	—	1	1200
102	20	Converse H ...	203*b*	1902	2105	1891-1900	3	23	2	—	×	×	×	—	2	700	0	—	2	700	—	—
103	11	Do	615*a*	1902	1287	1891-1900	3	4	11	—	×	×	×	—	0	—	0	—	0	—	—	—
104	17	Do	3*a*	1902	1899	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
105	20	Converse W. F...	258*b*	1892	2150	1881-1890	3	33	24	—	—	×	×	—	—	—	0	—	1	1100	—	—
106	22	Do ..	466*b*	1892	2358	1881-1890	3	129	89	—	—	×	×	—	—	—	0	—	4	470	—	—
107	4	Do ..	1344*a*	1892	548	1881-1890	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
108	4	Converse H	1369*a*	1892	523	1881-1890	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
109	5	Do	1206*a*	1892	686	1881-1890	1	—	—	—	×	—	—	—	1	340	—	—	—	—	—	—
110	6	Indian Basin ...	1151*a*	1903	752	1891-1900	1	—	—	—	×	—	—	—	1	370	—	—	—	—	—	—
111	6	Do	1109*a*	1903	794	1891-1900	1	—	—	—	×	—	—	—	1	400	—	—	—	—	—	—
112	2	Do	1520*a*	1903	383	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
113	3	Do	1423*a*	1903	480	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
114	17	Millwood.......	36*a*	1888	1852	1871-1880	3	25	12	—	—	×	×	—	—	—	0	—	1	900	—	—
115	17	Do	30*a*	1888	1858	1871-1880	3	34	6	—	×	—	×	—	0	—	—	—	0	—	—	—
116	29	Enterprise......	1191*b*	1876	3067	1861-1870	4	480	71	541	×	—	—	—	0	—	—	—	—	—	—	—
117	11	Do	614*a*	1892	1278	1881-1890	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
118	18	Do	94*b*	1893	1987	1881-1890	1	—	—	—	×	—	—	—	1	500	—	—	—	—	—	—
119	21	Do	300*b*	1890	2190	1881-1890	1	—	—	—	×	—	—	—	4	440	—	—	—	—	—	—
120	19	Do	153*b*	1893	2046	1881-1890	1	—	—	—	×	—	—	—	3	500	—	—	—	—	—	—
121	4	Do	1332*a*	1893	561	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
122	16	Mt. Home......	186*a*	1896	1710	1881-1890	2	30	—	—	×	×	—	—	0	400	3	—	—	—	—	—
123	26	Do	869*b*	1906	2775	1891-1900	2	17	—	—	×	×	—	—	0	900	0	—	—	—	—	—
124	25	Do	720*b*	1906	2626	1891-1900	2	41	—	—	×	×	—	—	0	—	4	520	—	—	—	—
125	13	Do	437*a*	1906	1469	1901-1910	1	—	—	—	×	—	—	—	2	490	—	—	—	—	—	—
126	13	Do	447*a*	1906	1459	1901-1910	1	—	—	—	×	—	—	—	2	490	—	—	—	—	—	—
127	18	Do	22*b*	1906	1928	1891-1900	2	26	—	—	×	×	—	—	0	480	3	—	—	—	—	—
128	22	Enterprise.....	437*b*	1895	2332	1881-1890	1	—	—	—	×	—	—	—	4	460	—	—	—	—	—	—
129	11	Coburn........	687*a*	1893	1206	1881-1890	2	68	—	—	×	—	—	—	0	...	Not used		...	...	...	...
130	13	Enterprise	448*a*	1893	1445	1881-1890	2	25	—	—	×	×	—	—	0	—	3	360	—	—	—	—
131	13	Coburn........	478*a*	1893	1415	1881-1890	1	—	—	—	×	—	—	—	2	470	—	—	—	—	—	—
132	16	Do........	181*a*	1893	1712	1881-1890	1	—	—	—	×	—	—	—	2	570	—	—	—	—	—	—
133	14	Do........	306*a*	1893	1587	1881-1890	2	28	—	—	×	×	—	—	0	—	3	530	—	—	—	—
134	1	Do........	1643*a*	1893	250	1881-1890	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
135	15	Do........	247*a*	1893	1646	1881-1890	2	8	—	—	×	×	—	—	0	—	0	—	—	—	—	—
136	16	Do........	179*a*	1890	1711	1881-1890	2	35	—	—	×	—	—	—	0	—	—	—	—	—	—	—
137	16	Do........	197*a*	1890	1693	1881-1890	1	—	—	—	×	—	—	—	2	570	—	—	—	—	—	—
138	8	Do........	929*a*	1890	961	1881-1890	1	—	—	—	×	—	—	—	1	480	—	—	—	—	—	—
139	6	Do........	1140*a*	1890	750	1881-1890	1	—	—	—	×	—	—	—	1	370	—	—	—	—	—	—
140	13	Do........	473*a*	1890	1417	1881-1890	2	21	—	—	×	×	—	—	2	470	0	—	—	—	—	—
141	15	Mt. Home......	225*a*	1906	1681	1891-1900	1	—	—	—	×	—	—	—	2	560	—	—	—	—	—	—
142	17	Do	60*a*	1903	1843	1891-1900	1	—	—	—	×	—	—	—	3	460	—	—	—	—	—	—
143	15	Do	227*a*	1903	1676	1891-1900	1	—	—	—	×	—	—	—	2	560	—	—	—	—	—	—
144	16	Do	200*a*	1903	1703	1891-1900	1	—	—	—	×	—	—	—	3	430	—	—	—	—	—	—
145	19	Do	155*b*	1904	2059	1891-1900	1	—	—	—	×	—	—	—	3	500	—	—	—	—	—	—
146	15	Do	237*a*	1904	1667	1891-1900	1	—	—	—	×	—	—	—	2	550	—	—	—	—	—	—
147	8	Do	928*a*	1904	976	1891-1900	1	—	—	—	×	—	—	—	1	490	—	—	—	—	—	—
148	8	Do	925*a*	1904	979	1891-1900	1	—	—	—	×	—	—	—	1	490	—	—	—	—	—	—
149	15	Do	220*a*	1896	1676	1881-1890	1	—	—	—	×	—	—	—	2	560	—	—	—	—	—	—
150	15	Dillonwood.....	272*a*	1898	1626	1891-1900	1	—	—	—	×	—	—	—	2	560	—	—	—	—	—	—
151	5	Do	1260*a*	1898	638	1881-1890	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
152	6	Do	1130*a*	1900	770	1891-1900	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
153	8	Do	907*a*	1900	993	1891-1900	2	0	—	—	×	×	—	—	0	—	0	—	—	—	—	—
154	11	Do	603*a*	1900	1307	1891-1900	2	26	—	—	×	×	—	—	0	—	2	430	—	—	—	—
155	17	Do	217*a*	1904	1687	1891-1900	1	—	—	—	×	—	—	—	2	560	—	—	—	—	—	—
156	18	Do	96*b*	1904	2000	1891-1900	1	—	—	—	×	—	—	—	1	1000	—	—	—	—	—	—
157	12	Do	563*a*	1909	1346	1901-1910	2	15	—	—	×	×	—	—	0	—	1	670	—	—	—	—
158	12	Do	549*a*	1909	1360	1901-1910	1	—	—	—	×	—	—	—	2	450	—	—	—	—	—	—
159	12	Do	596*a*	1909	1313	1901-1910	1	—	—	—	×	—	—	—	2	350	—	—	—	—	—	—
160	8	Do	972*a*	1909	937	1901-1910	1	—	—	—	×	—	—	—	1	470	—	—	—	—	—	—
161	8	Do	928*a*	1909	981	1901-1910	1	—	—	—	×	—	—	—	1	490	—	—	—	—	—	—
162	8	Do	915*a*	1909	994	1901-1910	1	—	—	—	×	—	—	—	1	500	—	—	—	—	—	—
163	9	Do	893*a*	1909	1016	1901-1910	1	—	—	—	×	—	—	—	1	500	—	—	—	—	—	—
164	8	Do	905*a*	1909	1004	1901-1910	1	—	—	—	×	—	—	—	1	500	—	—	—	—	—	—
165	1	Coburn.........	1671*a*	1906	235	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
166	1	Do.........	1681*a*	1906	225	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
167	11	Do........	689*a*	1905	1216	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
168																						
169	12	Coburn.........	597*a*	1900	1303	1891-1900	2	24	—	—	×	×	—	—	0	—	2	430	—	—	—	—
170	7	Dillonwood.....	1086*a*	1885	799	1871-1880	1	—	—	—	×	—	—	—	1	400	—	—	—	—	—	—
171	5	Do	1206*a*	1885	679	1871-1880	1	—	—	—	×	—	—	—	1	340	—	—	—	—	—	—
172	7	Do	1059*a*	1885	826	1871-1880	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
173	12	Do	590*a*	1885	1295	1871-1880	1	—	—	—	×	—	—	—	1	650	—	—	—	—	—	—
174	21	Do	354*b*	1902	2256	1891-1900	2	40	—	—	×	×	—	—	0	—	4	440	—	—	—	—

No.	Group.	Place.	First year of tree.	Year of cutting.	Age of tree at cutting.	Last decade measured.	No. of readings.	Difference between readings. A & B.	A & C.	A & D.	Readings to be used. A. B. C. D.	Decades to be added and intervals between them. A. Dec	A. Int.	B. Dec.	B. Int.	C. Dec.	C. Int	D. Dec.	D. Int.
175	16	Dillonwood	130*a*	1903	1776	1891-1900	2	240	—	—	Not used	—	—	—	—	—	—	—	—
176	16	Do	190*a*	1902	1271	1891-1900	2	11	—	—	× × — —	1	850	0	—	—	—	—	—
177	17	Do	49*a*	1880	1831	1871-1880	1	—	—	—	× — — —	3	430	—	—	—	—	—	—
178	16	Do	134*a*	1900	1766	1891-1900	2	7	—	—	× × — —	0	—	0	—	—	—	—	—
179	13	Do	422*a*	1910	1488	1901-1910	2	16	—	—	× × — —	0	—	2	490	—	—	—	—
180	20	Do	275*b*	1910	2181	1901-1910	2	6	—	—	× × — —	0	—	0	—	—	—	—	—
181	13	Do	480*a*	1900	1420	1891-1900	1	—	—	—	× — — —	2	470	—	—	—	—	—	—
182	14	Do	370*a*	1900	1530	1891-1900	1	—	—	—	× — — —	2	510	—	—	—	—	—	—
183	16	Frasier	181*a*	1903	1707	1891-1900	2	28	—	—	× × — —	3	530	0	—	—	—	—	—
184	16	Do	193*a*	1898	1705	1891-1900	2	15	—	—	× × — —	0	530	2	—	—	—	—	—
185	13	Dillonwood	442*a*	1898	1446	1891-1900	2	7	—	—	× × — —	0	—	0	—	—	—	—	—
186	13	Do	431*a*	1888	1457	1881-1890	2	19	—	—	× × — —	0	—	2	490	—	—	—	—
187	20	Frasier	288*b*	1888	2176	1881-1890	2	5	—	—	× × — —	0	—	0	—	—	—	—	—
188	15	Do	252*a*	1890	1638	1881-1890	1	—	—	—	× — — —	2	530	—	—	—	—	—	—
189	15	Do	279*a*	1890	1611	1881-1890	1	—	—	—	× — — —	2	530	—	—	—	—	—	—
190	16	Enterprise	165*a*	1893	1728	1881-1890	1	—	—	—	× — — —	3	430	—	—	—	—	—	—
191	15	Do	265*a*	1893	1628	1881-1890	1	—	—	—	× — — —	2	530	—	—	—	—	—	—
192	23	Do	533*b*	1893	2426	1881-1890	1	—	—	—	× — — —	4	490	—	—	—	—	—	—
193	23	Do	541*b*	1893	2437	1881-1890	1	—	—	—	× — — —	4	490	—	—	—	—	—	—
194	23	Do	568*b*	1893	2461	1881-1890	1	—	—	—	× — — —	2	980	—	—	—	—	—	—
195	29	Do	1141*b*	1893	3034	1881-1890	1	—	—	—	× — — —	6	370	—	—	—	—	—	—
196	26	Do	876*b*	1893	2769	1881-1890	1	—	—	—	× — — —	2	400	—	—	—	—	—	—
197-200	No statistics for these Nos.																		
201	10	Hume	701*a*	1911	1210	1901-1910	4	33	45	35	— × × ×	—	—	1	630	0	—	1	630
202	5	Do	1290*a*	1911	621	1901-1910	3	21	29	—	— × × —	—	—	0	—	0	—	—	—
203	5	Do	1205*a*	1911	706	1901-1910	3	8	15	—	— × × —	—	—	1	350	0	—	—	—
204	5	Do	1189*a*	1911	722	1901-1910	2	15	—	—	× — — —	0	—	—	—	—	—	—	—
205	5	Do	1228*a*	1911	683	1901-1910	1	—	—	—	× — — —	1	350	—	—	—	—	—	—
206	4	Do	1379*a*	1911	532	1901-1910	2	1	—	—	× × — —	0	—	0	—	—	—	—	—
207	3	Do	1482*a*	1911	429	1901-1910	2	0	—	—	× × — —	0	—	0	—	—	—	—	—
208	5	Do	1217*a*	1911	694	1901-1910	2	12	—	—	× × — —	0	—	1	350	—	—	—	—
209	3	Do	1482*a*	1911	429	1901-1910	2	0	—	—	× × — —	0	—	0	—	—	—	—	—
210	6	Do	1137*a*	1911	774	1901-1910	1	0	—	—	× — — —	1	380	—	—	—	—	—	—
211	2	Do	1578*a*	1911	333	1901-1910	2	2	—	—	× × — —	0	—	0	—	—	—	—	—
212	1	Do	1620*a*	1911	291	1901-1910	2	3	—	—	× × — —	0	—	0	—	—	—	—	—
213	6	Do	1124*a*	1911	787	1901-1910	2	15	—	—	— × — —	—	—	0	—	—	—	—	—
214	3	Do	1463*a*	1911	448	1901-1910	2	8	—	—	× × — —	0	—	0	—	—	—	—	—
215	9	Comstock	896*a*	1891	995	1881-1890	2	5	—	—	× × — —	0	—	0	—	—	—	—	—
216	17	Do	54*a*	1891	1837	1881-1890	2	10	—	—	× × — —	0	—	1	900	—	—	—	—
217	4	Do	1353*a*	1891	538	1881-1890	2	0	—	—	× × — —	0	—	0	—	—	—	—	—
218	13	Do	481*a*	—	—	....	1	—	—	—	Not used								
219	8	Do	942*a*	1891	949	1881-1890	3	25	3	—	— × — —	—	—	0	—	—	—	—	—
220	7	Do	1026*a*	1890	864	1881-1890	2	9	—	—	× × — —	0	—	1	420	—	—	—	—
221	4	Do	1318*a*	1891	573	1881-1890	3	11	31	—	× — × —	0	—	—	—	1	280	—	—
222	4	Do	1314*a*	1891	577	1881-1890	4	21	32	—	Not used								
223	7	Do	1052*a*	1891	839	1881-1890	2	6	—	—	× × — —	0	—	0	—	—	—	—	—
224	7	Do	1004*a*	1891	887	1881-1890	3	19	46	—	× — — —	0	—	—	—	—	—	—	—
225	4	Do	1339*a*	1891	552	1881-1890	2	10	—	—	× × — —	1	270	0	—	—	—	—	—
226	4	Do	1333*a*	1891	558	1881-1890	3	10	2	—	× × × —	—	—	0	—	1	270	—	—
227	4	Do	1291*a*	1891	597	1881-1890	4	29	8	5	× — — —	0	—	—	—	—	—	—	—
228	4	Do	1348*a*	1891	543	1881-1890	2	3	—	—	× × — —	0	—	0	—	—	—	—	—
229	12	Do	516*a*	1891	1375	1881-1890	2	3	—	—	× × — —	0	—	0	—	—	—	—	—
230	4	Do	1359*a*	1891	532	1881-1890	2	4	—	—	× × — —	0	—	0	—	—	—	—	—
231	7	Do	1099*a*	1891	792	1881-1890	2	2	—	—	× × — —	0	—	0	—	—	—	—	—
232	9	Do	839*a*	1891	1052	1881-1890	4	10	1	20	× × × —	0	—	1	500	0	—	—	—
233	14	Do	300*a*	1891	1591	1881-1890	4	140	10	57	Not used								
234	4	Do	1323*a*	1891	568	1881-1890	2	8	—	—	× × — —	0	—	0	—	—	—	—	—
235	4	Do	1334*a*	1891	557	1881-1890	2	67	—	—	— × — —	—	—	0	—	—	—	—	—
236	8	Do	920*a*	1891	971	1881-1890	2	9	—	—	× × — —	1	480	0	—	—	—	—	—
237	8	Do	925*a*	1891	966	1881-1890	2	17	—	—	× × — —	0	—	1	300	—	—	—	—
238	4	Do	1344*a*	1891	547	1881-1890	2	1	—	—	× × — —	0	—	0	—	—	—	—	—
239	18	Do	44*b*	1880	1924	1871-1880	2	24	—	—	× × — —	2	630	0	—	—	—	—	—
240	15	Do	256*a*	1891	1634	1881-1890	3	70	3	—	× — — —	0	—	—	—	—	—	—	—
241	3	Do	1462*a*	1891	429	1881-1890	2	3	—	—	× × — —	0	—	0	—	—	—	—	—
242	4	Do	1326*a*	1891	565	1881-1890	3	25	12	—	× — × —	0	—	—	—	1	280	—	—
243	4	Do	1349*a*	1891	542	1881-1890	3	27	69	—	Not used								
244	15	Do	264*a*	1891	1627	1881-1890	3	63	11	—	× — × —	0	—	—	—	1	800	—	—
245	4	Do	1355*a*	1890	535	1881-1890	3	9	1	—	× × × —	1	150	0	—	1	300	—	—
246	11	Do	657*a*	1891	1234	1881-1890	3	50	21	—	× — × —	0	—	—	—	2	400	—	—
247	11	Do	602*a*	1886	1284	1871-1880	2	2	—	—	× × — —	0	—	0	—	—	—	—	—
248	10	Do	751*a*	1891	1140	1881-1890	2	10	—	—	× × — —	0	—	1	570	—	—	—	—
249	11	Do	611*a*	1890	1279	1881-1890	2	10	—	—	× × — —	0	—	1	660	—	—	—	—
250	9	Do	803*a*	1890	1087	1881-1890	2	0	—	—	× × — —	0	—	0	—	—	—	—	—
251	9	Do	800*a*	1891	1091	1881-1890	3	19	14	—	× — × —	0	—	—	—	2	360	—	—
252	9	Do	810*a*	1890	1080	1881-1890	3	34	15	—	— × × —	—	—	0	—	2	540	—	—
253	10	Do	760*a*	1890	1130	1881-1890	2	10	—	—	× × — —	1	560	0	—	—	—	—	—
254	11	Do	637*a*	1890	1253	1881-1890	3	97	2	—	× — × —	0	—	—	—	0	—	—	—
255	8	Do	912*a*	1891	979	1881-1890	2	4	—	—	× × — —	0	—	0	—	—	—	—	—
256	4	Do	1319*a*	1887	568	1871-1880	2	5	—	—	× × — —	1	270	0	—	—	—	—	—
257	4	Do	1326*a*	1880	554	1871-1880	2	2	—	—	× × — —	0	—	0	—	—	—	—	—
258	4	Do	1301*a*	1886	585	1871-1880	2	2	—	—	× × — —	0	—	0	—	—	—	—	—
259	12	Do	596*a*	1890	1294	1881-1890	3	35	22	—	— × × —	—	—	0	—	1	640	—	—
260	4	Do	1336*a*	1890	554	1881-1890	3	16	6	—	— × × —	—	—	0	—	1	270	—	—
261	4	Do	1331*a*	1890	559	1881-1890	2	3	—	—	× × — —	0	—	0	—	—	—	—	—
262	4	Do	1324*a*	1885	561	1871-1880	2	4	—	—	× × — —	0	—	0	—	—	—	—	—
263	12	Wigger	517*a*	1886	1369	1881-1890	3	7	8	—	× × × —	0	—	1	680	1	680	—	—
264	21	Do	333*b*	1890	2223	1881-1890	4	206	213	33	Not used								
265	11	Do	622*a*	1890	1268	1881-1890	3	30	19	—	— × × —	—	—	0	—	1	630	—	—

No.	Group.	Place.	First year of tree.	Year of cutting.	Age of tree at cutting.	Last decade measured.	No. of readings.	Difference between readings. A & B.	A & C.	A & D.	Readings to be used. A.	B.	C.	D.	Decades to be added and intervals between them. A. Dec.	A. Int.	B. Dec.	B. Int.	C. Dec.	C. Int.	D. Dec.	D. Int.
266	11	Wigger	625*a*	1890	1265	1881-1890	2	19	—	—	×	×	—	—	2	410	0	—	—	—	—	—
267	11	Do	606*a*	1890	1284	1881-1890	2	8	—	—	×	×	—	—	0	—	1	640	—	—	—	—
268	12	Do	533*a*	1890	1357	1881-1890	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
260	13	Do	493*a*	1890	1397	1881-1890	2	12	—	—	×	×	—	—	1	700	—	—	—	—	—	—
270	14	Do	373*a*	1890	1517	1881-1890	2	26	—	—	×	×	—	—	0	—	2	500	—	—	—	—
271	14	Do	376*a*	1890	1514	1881-1890	2	8	—	—	×	×	—	—	0	—	1	750	—	—	—	—
272	20	Do	202*b*	1890	2092	1881-1890	2	36	—	—	×	—	—	—	0	—	—	—	—	—	—	—
273	10	Do	779*a*	1890	1121	1881-1890	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
274	13	Do	446*a*	1890	1444	1881-1890	2	98	—	—	Not used				....	....	....	....	....	....	....	....
275	13	Do	403*a*	1890	1487	1881-1890	2	28	—	—	×	—	—	—	0	—	0	—	—	—	—	—
276	18	Do	18*b*	1890	1908	1881-1890	2	9	—	—	×	×	—	—	0	—	0	—	—	—	—	—
277	7	Do	1005*a*	1890	1885	1881-1890	2	8	—	—	×	×	—	—	0	—	0	—	—	—	—	—
278	17	Do	11*a*	1890	1879	1881-1890	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
279	9	Do	892*a*	1890	998	1881-1890	2	7	—	—	×	×	—	—	0	—	0	—	—	—	—	—
280	8	Do	904*a*	1890	986	1881-1890	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
281	13	Do	449*a*	1891	1442	1881-1890	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
282	14	Do	311*a*	1890	1579	1881-1890	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
283	4	Do	1317*a*	1890	573	1881-1890	2	6	—	—	×	×	—	—	0	—	0	—	—	—	—	—
284	11	Do	606*a*	1891	1285	1881-1890	2	12	—	—	×	×	—	—	0	—	1	640	—	—	—	—
285	16	Do	177*a*	1890	1713	1881-1890	2	24	—	—	×	×	—	—	0	—	2	570	—	—	—	—
286	22	Do	479*b*	1890	2370	1881-1890	2	18	—	—	×	×	—	—	0	—	0	—	—	—	—	—
287	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
288	11	Wigger	641*a*	1890	1249	1881-1890	2	23	—	—	Not used				....	....	....	....	....	....	....	....
289	16	Do	128*c*	1890	1762	1881-1890	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
290	7	Do	1009*a*	1890	881	1881-1890	2	6	—	—	×	×	—	—	0	—	0	—	—	—	—	—
291	14	Do	337*a*	1890	1553	1881-1890	2	15	—	—	×	×	—	—	2	510	0	—	—	—	—	—
292	14	Do	347*a*	1890	1543	1831-1890	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
293	13	Do	459*a*	1890	1431	1881-1890	2	64	—	—	Not used				....	....	....	....	....	....	....	....
294	8	Do	912*a*	1890	978	1881-1890	2	9	—	—	×	×	—	—	0	—	0	—	—	—	—	—
295	4	Comstock	1320*a*	1887	567	1871-1880	4	23	1	8	×	—	×	—	0	—	—	—	0	—	—	—
296	4	Do	1337*a*	1890	553	1881-1890	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
297	4	Do	1327*a*	1880+	553	1871-1880	4	23	2	5	×	—	×	×	1	270	—	—	0	—	0	—
298	4	Do	1330*a*	1890	560	1881-1890	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
299	4	Do	1333*a*	1886	553	1871-1880	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
300	4	Do	1310*a*	1800	580	1881-1890	2	18	—	—	—	×	—	—	—	—	0	—	—	—	—	—
301	4	Do	1214*a*	1890	676	1881-1890	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
302	6	Do	1119*a*	1890	771	1881-1890	2	6	—	—	×	×	—	—	0	—	0	—	—	—	—	—
303	26	Do	847*b*	1905	2752	1891-1900	4	182	54	271	×	—	×	—	5	450	—	—	0	—	—	—
304	27	Converse W. F.	963*b*	1902	2865	1891-1900	2	8	—	—	×	×	—	—	0	—	0	—	—	—	—	—
305	17	Converse H.	89*a*	1906	1817	1891-1900	3	70	87	—	—	×	×	—	—	—	1	900	0	—	—	—
306	12	Do	551*a*	1900	1349	1891-1900	2	92	—	—	×	—	—	—	0	—	—	—	—	—	—	—
307	20	Do	243*b*	1900	2143	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
308	10	Do	766*a*	1892	1126	1881-1890	2	0	—	—	×	×	—	—	0	—	0	—	—	—	—	—
309	19	Do	199*b*	1892	2091	1881-1890	3	72	7	—	—	×	×	—	—	—	0	—	0	—	—	—
310	11	Do	633*a*	1892	1259	1881-1890	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
311	12	Do	586*a*	1904	1318	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
312	11	Converse T. S.	614*a*	1901	1287	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
313	12	Do	566*a*	1904	1338	1891-1900	3	11	25	—	×	×	—	—	0	—	1	700	—	—	—	—
314	18	Do	81*b*	1904	1985	1891-1900	3	20	51	—	×	×	—	—	0	—	2	630	—	—	—	—
315	18	Do	87*b*	1904	1991	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
316	8	Do	968*a*	1904	936	1891-1900	2	10	—	—	×	×	—	—	1	450	0	—	—	—	—	—
317	18	Do	19*b*	1904	1923	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
318	20	Do	266*b*	1904	2170	1891-1900	2	20	—	—	×	×	—	—	0	—	2	700	—	—	—	—
319	16	Do	152*a*	1904	1752	1891-1900	2	12	—	—	×	×	—	—	0	—	1	800	—	—	—	—
320	21	Do	310*b*	1904	2214	1891-1900	2	15	—	—	×	×	—	—	1	1100	0	—	—	—	—	—
321	11	Do	611*a*	1904	1393	1891-1900	2	13	—	—	×	×	—	—	0	—	1	630	—	—	—	—
322	11	Do	653*a*	1904	1251	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
323	17	Do	89*a*	1904	1815	1891-1900	3	66	31	—	×	—	×	—	0	—	—	—	3	460	—	—
324	17	Do	98*a*	1904	1806	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
325	12	Do	511*a*	1904	1393	1891-1900	2	13	—	—	×	×	—	—	0	—	1	700	—	—	—	—
326	17	Converse Mill	97*a*	1901	1804	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
327	17	Do	37*a*	1901	1864	1891-1900	2	16	—	—	×	×	—	—	0	—	2	610	—	—	—	—
328	17	Do	44*a*	1901	1857	1891-1900	3	31	17	—	×	—	×	—	0	—	—	—	1	900	—	—
329	16	Do	170*a*	1901	1731	1891-1900	3	27	21	—	×	—	×	—	0	—	—	—	2	580	—	—
330	7	Do	1035*a*	1901	866	1891-1900	2	12	—	—	×	×	—	—	1	400	0	—	—	—	—	—
331	9	Converse T. S.	834*a*	1904	1070	1891-1900	3	34	11	—	×	—	×	—	1	520	—	—	0	—	—	—
332	19	Converse H.	183*b*	1901	2084	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
333	11	Do	650*a*	1901	1251	1891-1900	2	11	—	—	×	×	—	—	0	—	1	600	—	—	—	—
334	14	Converse Mill	372*a*	1901	1529	1891-1900	2	6	—	—	×	×	—	—	0	—	0	—	—	—	—	—
335	20	Do	253*b*	1901	2154	1891-1900	2	19	—	—	×	×	—	—	0	—	1	1000	—	—	—	—
336	12	Do	503*a*	1901	1398	1891-1900	2	13	—	—	×	×	—	—	1	700	0	—	—	—	—	—
337	10	Do	744*a*	1901	1157	1891-1900	2	8	—	—	×	×	—	—	0	—	0	—	—	—	—	—
338	10	Do	767*a*	1901	1134	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
339	12	Do	573*a*	1901	1327	1891-1900	3	0	42	—	—	×	×	—	—	—	0	—	—	—	—	—
340	20	Do	215*b*	1901	2116	1891-1900	3	57	8	—	—	×	—	—	—	—	0	—	—	—	—	—
341	16	Do	103*a*	1901	1798	1891-1900	2	14	—	—	×	×	—	—	1	990	0	—	—	—	—	—
342	12	Do	581*a*	1901	1320	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
343	17	Converse H.	24*a*	1892	1868	1881-1890	2	11	—	—	×	×	—	—	0	—	1	900	—	—	—	—
344	15	Converse Mill	206*a*	1901	1695	1891-1900	3	21	2	—	×	—	×	—	0	—	—	—	0	—	—	—
345	10	Converse No. 6	772*a*	1905	1133	1891-1900	2	7	—	—	×	×	—	—	0	—	0	—	—	—	—	—
346	15	Do	281*a*	1903	1622	1891-1900	3	20	10	—	×	—	×	—	0	—	—	—	1	800	—	—
347	14	Do	360*a*	1901	1541	1891-1900	2	9	—	—	×	×	—	—	0	—	1	770	—	—	—	—
348	14	Do	366*a*	1903	1537	1891-1900	2	16	—	—	×	×	—	—	1	750	0	—	—	—	—	—
349	9	Converse Mill	889*a*	1903	1014	1891-1900	3	17	25	—	×	×	—	—	0	—	2	330	—	—	—	—
350	20	Converse H.	272*b*	1901	2173	1891-1900	3	121	33	—	×	—	×	—	0	—	—	—	3	400	—	—
351	15	Do	220*a*	1901	1681	1891-1900	2	10	—	—	×	×	—	—	1	800	0	—	—	—	—	—
352	11	Do	695*a*	1901	1216	1881-1900	2	15	—	—	×	×	—	—	0	—	1	600	—	—	—	—
353	18	Converse Mill	44*b*	1901	1945	1891-1900	3	228	1	—	—	×	×	—	—	—	0	—	0	—	—	—

No.	Group.	Place.	First year of tree.	Year of cutting.	Age of tree at cutting.	Last decade measured.	No. of readings.	Difference between readings.			Readings to be used.				Decades to be added and intervals between them.							
								A & B.	A & C.	A & D.	A.	B.	C.	D.	A. Dec.	A. Int.	B. Dec.	B. Int.	C. Dec.	C. Int.	D. Dec.	D. Int.
354	16	Converse Mill	141a	1901	1760	1891-1900	3	102	40	—	—	—	×	—	—	—	—	—	0	—	—	—
355	20	Converse H.	280b	1892	2172	1881-1890	3	31	36	—	×	×	×	—	4	440	1	1100	0	—	—	—
356	12	Do	583a	1892	1309	1881-1890	2	8	—	—	×	×	—	—	1	700	0	—	—	—	—	—
357	20	Converse Mill	252b	1901	2153	1891-1900	2	21	—	—	×	×	—	—	2	710	0	—	—	—	—	—
358	14	Do	304a	1901	1597	1891-1900	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
359	12	Do	581a	1901	1320	1891-1900	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
360	11	Do	698a	1901	1203	1891-1900	2	13	—	—	×	×	—	—	1	600	0	—	—	—	—	—
361	10	Do	726a	1901	1175	1891-1900	2	13	—	—	×	×	—	—	0	—	1	580	—	—	—	—
362	11	Do	622a	1901	1279	1891-1900	3	19	10	—	×	—	×	—	0	—	—	—	1	650	—	—
363	12	Do	589a	1901	1312	1891-1900	2	0	—	—	×	×	—	—	0	—	0	—	—	—	—	—
364	15	Do	201a	1901	1700	1891-1900	3	219	19	—	×	—	×	—	0	—	—	—	2	550	—	—
365	9	Converse No. 6	855a	1905	1050	1891-1900	2	0	—	—	×	×	—	—	0	—	0	—	—	—	—	—
366	10	Do	702a	1003	1201	1891-1900	2	6	—	—	×	×	—	—	0	—	0	—	—	—	—	—
367	12	Do	511a	1903	1392	1891-1900	2	5	—	—	×	×	—	—	0	—	1	700	—	—	—	—
368	19	Do	185b	1903	2088	1891-1900	3	35	10	—	—	×	×	—	—	—	0	—	2	700	—	—
369	12	Converse Camp No. 1	534a	1902	1368	1891-1900	1	—	—	—	×	—	—	—	0	—	—	—	—	—	—	—
370	9	Converse Mill	862a	1903	1041	1891-1900	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
371	11	Converse No. 1	652a	1904	1252	1891-1900	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
372	13	Do	462a	1904	1442	1891-1900	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
373	15	Do	225a	1904	1679	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
374	20	Do	257b	1904	2161	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
375	23	Do	509b	1904	2413	1891-1900	2	9	—	—	×	×	—	—	0	—	0	—	—	—	—	—
376	13	Converse W. F.	469a	1902	1442	1891-1900	3	26	38	—	×	×	—	—	0	—	3	350	—	—	—	—
377	13	Do	415a	1902	1487	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
378	14	Do	347a	1902	1555	1891-1900	2	15	—	—	×	×	—	—	1	750	0	—	—	—	—	—
379	11	Do	690a	1902	1212	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
380	11	Do	608a	1903	1295	1891-1900	2	46	—	—	×	—	—	—	0	—	—	—	—	—	—	—
381	19	Converse R. Roy	156b	1904	2060	1891-1900	3	66	9	—	×	—	×	—	0	—	—	—	0	—	—	—
382	20	Converse No. 1	233b	1904	2137	1891-1900	3	34	0	—	×	—	×	—	0	—	—	—	0	—	—	—
383	13	Do	491a	1904	1413	1891-1900	3	44	8	—	×	—	×	—	0	—	—	—	1	700	—	—
384	23	Do	520b	1904	2424	1891-1900	2	8	—	—	×	×	—	—	1	1200	0	—	—	—	—	—
385	17	Do	56a	1904	1848	1891-1900	2	41	—	—	Not used				....	....	....	....	....	....	....	....
386	22	Do	490b	1904	2394	1891-1900	3	93	77	—	×	—	—	—	0	—	—	—	—	—	—	—
387	22	Do	482b	1904	2386	1891-1900	2	11	—	—	×	×	—	—	0	—	1	1200	—	—	—	—
388	24	Do	636b	1903	2539	1891-1900	2	29	—	—	×	×	—	—	0	—	3	500	—	—	—	—
389	20	Do	273b	1903	2176	1891-1900	3	168	45	—	×	—	—	—	0	—	—	—	—	—	—	—
390	23	Converse W. F.	504b	1894	2408	1881-1890	2	20	—	—	×	×	—	—	0	—	2	800	—	—	—	—
391	21	Do	376b	1892	2268	1881-1890	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
392	7(14)	Boule	388a	1904	1516	1891-1900	4	16	17	13	×	—	×	—	0	—	—	—	2	500	—	—
393	......	See No. 13	....	....	....	....	....	....	....	....	....				....	....	....	....	....	....	....	....
394	8(?)11	Boule	687a	1904	1217	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
395	9	Boule Camp No. 4	832a	1904	1072	1891-1900	3	24	25	—	×	—	×	—	0	—	—	—	0	—	—	—
396	10	Converse Camp No. 4	776a	1904	1128	1891-1900	2	10	—	—	×	×	—	—	0	—	0	—	—	—	—	—
397	19	Converse Camp No. 1	136b	1900	2036	1891-1900	2	10	—	—	×	×	—	—	0	—	1	1000	—	—	—	—
398	20	Do	211b	1900	2111	1891-1900	3	65	11	—	×	—	×	—	0	—	—	—	1	1050	—	—
399	20	Do	240b	1900	2140	1891-1900	2	7	—	—	×	×	—	—	0	—	1	1100	—	—	—	—
400	10	Converse W. F.	782a	1902	1120	1891-1900	2	9	—	—	×	×	—	—	0	—	1	550	—	—	—	—
401	15	Do	234a	1902	1668	1891-1900	2	17	—	—	×	×	—	—	0	—	1	500	—	—	—	—
402	18(20)	Boule	258b	1904	2162	1891-1900	3	95	88	—	—	×	×	—	—	—	0	—	1	1100	—	—
403	17(19)	Do	199b	1904	2103	1891-1900	3	43	59	—	—	×	×	—	—	—	1	1050	0	—	—	—
404	13	Converse No. 4	435a	1904	1469	1891-1900	2	9	—	—	×	×	—	—	1	700	0	—	—	—	—	—
405	11	Do	689a	1904	1215	1891-1900	2	13	—	—	×	×	—	—	0	—	1	600	—	—	—	—
406	11	Do	651a	1904	1253	1891-1900	2	37	—	—	×	—	—	—	0	—	—	—	—	—	—	—
407	21	Converse Camp No. 1	332b	1900	2232	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
408	18	Do	78b	1900	1978	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
409	21	Do	315b	1900	2215	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
410	17	Do	33a	1902	1869	1891-1900	4	51	31	25	—	—	×	×	—	—	—	—	0	—	0	—
411	23	Converse W. F.	589b	1902	2491	1891-1900	3	120	15	—	×	—	×	—	0	—	—	—	1	1200	—	—
412	9	Do	821a	1902	1081	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
413	11	Do	612a	1902	1290	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
414	17	Do	31a	1902	1871	1891-1900	3	162	19	—	×	—	×	—	0	—	—	—	2	650	—	—
415	15	Do	278a	1902	1624	1891-1900	2	8	—	—	×	×	—	—	0	—	0	—	—	—	—	—
416	15	Do	266a	1902	1636	1891-1900	2	9	—	—	×	×	—	—	1	820	0	—	—	—	—	—
417	11	Do	613a	1902	1289	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
418	12	Do	588a	1902	1314	1891-1900	3	40	14	—	×	—	×	—	0	—	—	—	1	650	—	—
419	10	Do	763a	1902	1139	1891-1900	2	11	—	—	×	×	—	—	1	550	0	—	—	—	—	—
420	15	Do	286a	1902	1616	1891-1900	2	31	—	—	×	×	—	—	3	400	0	—	—	—	—	—
421	22	Converse Camp No. 1	413b	1902	2315	1891-1900	2	48	—	—	×	×	—	—	4	450	0	—	—	—	—	—
422	25	Converse Mill	719b	1902	2621	1891-1900	3	24	78	—	×	×	—	—	2	850	0	—	—	—	—	—
423	17	Converse W. F.	47a	1902	1855	1891-1900	2	11	—	—	×	×	—	—	0	—	1	900	—	—	—	—
424	11	Do	659a	1902	1243	1891-1900	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
425	19	Do	196b	1902	2098	1891-1900	2	12	—	—	×	×	—	—	0	—	1	1050	—	—	—	—
426	13	Do	432a	1902	1470	1891-1900	2	16	—	—	×	×	—	—	1	730	0	—	—	—	—	—
427	15	Do	209a	1902	1693	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
428	11	Do	652a	1902	1250	1891-1900	3	19	5	—	×	×	—	—	2	420	0	—	—	—	—	—
429	11	Do	605a	1902	1297	1891-1900	2	11	—	—	×	×	—	—	0	—	1	650	—	—	—	—
430	22	Converse Mill	438b	1901	2339	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
431	9	Converse W. F.	875a	1902	1027	1891-1900	2	23	—	—	×	×	—	—	0	—	2	340	—	—	—	—
432	12	Converse H.	551a	1902	1351	1891-1900	2	1	—	—	×	×	—	—	0	—	0	—	—	—	—	—
433	21	Converse W. F.	325b	1902	2227	1891-1900	2	59	—	—	—	×	—	—	—	—	0	—	—	—	—	—
434	20	Converse No. 1.	270b	1903	2173	1891-1900	2	3	—	—	×	×	—	—	0	—	2	700	—	—	—	—
435	20	Converse W. F.	208b	1902	2110	1891-1900	2	19	—	—	×	×	—	—	0	—	2	700	—	—	—	—
436	14	Converse No. 1	376a	1900	1524	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
437	9	Do	806a	1900	1094	1891-1900	2	7	—	—	×	×	—	—	1	550	0	—	—	—	—	—
438	13	Do	439a	1900	1461	1891-1900	2	10	—	—	×	×	—	—	0	—	1	700	—	—	—	—
439	14	Do	357a	1900	1543	1891-1900	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
440	10	Do	764a	1900	1136	1891-1900	2	6	—	—	×	×	—	—	0	—	0	—	—	—	—	—
441	10	Do	713a	1900	1187	1891-1900	2	10	—	—	×	×	—	—	1	600	0	—	—	—	—	—

No.	Group.	Place.	First year of tree.	Year of cutting.	Age of tree at cutting.	Last decade measured.	No. of readings.	Difference between readings. A & B.	A & C.	A & D.	Readings to be used. A.	B.	C.	D.	Decades to be added and intervals between them. A. Dec.	A. Int.	B. Dec.	B. Int.	C. Dec.	C. Int.	D. Dec.	D. Int.
442	10	Converse No. 1.......	705a	1900	1195	1891-1900	2	9	—	—	×	×	—	—	1	600	0	—	—	—	—	—
443	14	Converse Mill.......	333a	1901	1568	1891-1900	2	12	—	—	×	×	—	—	0	—	1	800	—	—	—	—
444	14	Do	303a	1901	1598	1891-1900	2	11	—	—	×	×	—	—	1	800	0	—	—	—	—	—
445	16	Do	102a	1901	1799	1891-1900	2	13	—	—	×	×	—	—	0	—	1	900	—	—	—	—
446	17	Do	65a	1901	1836	1891-1900	2	14	—	—	×	×	—	—	0	—	1	900	—	—	—	—
447	11	Do	617a	1896	1279	1881-1890	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
448	17	Do	70a	1901	1831	1891-1900	2	11	—	—	×	×	—	—	1	900	0	—	—	—	—	—
449	16	Do	150a	1901	1751	1891-1900	2	10	—	—	×	×	—	—	0	—	1	850	—	—	—	—
450	11	Do	687a	1901	1214	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
451	14	Do	389a	1901	1512	1891-1900	2	15	—	—	×	×	—	—	0	—	1	800	—	—	—	—
452	17	Converse No. 1.	26b	1900	1926	1891-1900	3	72	62	—	—	×	×	—	—	—	0	—	1	900	—	—
453	17	Do	31a	1900	1869	1891-1900	2	18	—	—	×	×	—	—	0	—	2	600	—	—	—	—
454	14	Do	364a	1900	1536	1891-1900	2	0	—	—	×	×	—	—	0	—	0	—	—	—	—	—
455	18	Do	33b	1900	1933	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
456	9	Do	804a	1900	1096	1891-1900	2	12	—	—	×	×	—	—	2	350	0	—	—	—	—	—
457	14	Do	367a	1900	1533	1891-1900	2	74	—	—	×	—	—	—	0	—	—	—	—	—	—	—
458	14	Do	364a	1900	1536	1891-1900	2	102	—	—	×	—	—	—	0	—	—	—	—	—	—	—
459	13	Do	422a	1900	1478	1891-1900	3	22	11	—	—	×	×	—	—	—	0	—	1	750	—	—
460	13	Do	427a	1900	1473	1891-1900	2	8	—	—	×	×	—	—	0	—	1	750	—	—	—	—
461	12	Converse Mill	560a	1901	1341	1891-1900	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
462	12	Do	582a	1901	1319	1891-1900	2	0	—	—	×	×	—	—	0	—	0	—	—	—	—	—
463	14	Do	392a	1901	1509	1891-1900	2	4	—	—	×	×	—	—	0	—	0	—	—	—	—	—
464	15	Do	204a	1901	1699	1891-1900	2	7	—	—	×	×	—	—	0	—	0	—	—	—	—	—
465	15	Do	274a	1901	1627	1891-1900	2	10	—	—	×	×	—	—	0	—	1	800	—	—	—	—
466	14	Do	336a	1901	1565	1891-1900	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
467	12	Do	528a	1901	1373	1891-1900	2	3	—	—	×	×	—	—	0	—	0	—	—	—	—	—
468	13	Do	418a	1901	1483	1891-1900	2	5	—	—	×	×	—	—	0	—	0	—	—	—	—	—
469	16	Do	182a	1901	1719	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—
470	12	Do	505a	1901	1396	1891-1900	2	2	—	—	×	×	—	—	0	—	0	—	—	—	—	—

Note on Location of Places.—Aside from Millwood and Hume, the localities here mentioned are merely local names of mills, etc. They may be grouped as follows: (A) Millwood east of Sanger; (B) Parts of Converse Basin north of Millwood, viz, Boule, Rob Roy, T. S. = Three Sisters, H = Hoist, W. F. = World's Fair Tree district; (C) Indian Basin between Converse Basin and Hume; (D) Hume; (E) Enterprise, Coburo, Frasier, and Mountain Home east of Portersville; (F) Dillonwood north of (E); (G) Comstock and Wigger, southeast of Millwood; (H) Eldorado in Calaveras County.

TABLE D.—*Summary of Sequoia Trees, by Groups.*

Group	Average age.	No. of trees	No. of measurements. Used.	Not used.	No. of trees having more than one measurement.	Diff. of 1st and 2d readings—years. Total.	Average.	Decades added. No. of cases.	Total No. of decades.
1	250	6	7	0	1	3	3	0	0
2	350	7	8	0	1	2	2	0	0
3	450	11	15	0	4	11	3	0	0
4	550	37	63	9	26	286	11	9	9
5	650	16	21	3	6	64	11	9	9
6	750	8	10	1	3	22	7	5	5
7	850	11	17	2	7	72	10	5	5
8	950	19	26	2	8	76	9	13	13
9	1,050	22	42	6	15	195	13	14	19
10	1,150	20	42	2	20	188	9	13	13
11	1,250	38	75	8	37	589	16	18	22
12	1,350	32	59	10	27	332	12	16	19
13	1,450	28	49	7	22	353	16	22	35
14	1,550	28	51	9	26	488	19	14	21
15	1,650	29	47	12	19	611	32	21	36
16	1,750	20	33	4	15	335	22	15	29
17	1,850	24	47	12	22	652	30	15	24
18	1,950	16	30	5	13	459	35	8	14
19	2,050	15	25	7	10	384	38	11	23
20	2,150	26	49	15	25	946	38	18	34
21	2,250	9	17	1	8	139	17	4	11
22	2,350	12	24	10	11	441	40	9	24
23	2,450	7	11	1	4	157	39	6	14
24	2,550	1	2	0	1	29	29	1	3
25	2,650	2	4	1	2	65	33	2	6
26	2,750	3	5	2	2	197	99	2	7
27	2,850	1	2	0	1	8	8	0	0
28	....	......	......	......	......	......	......	......	......
29	3,050	1	1	0	0	......	.....	1	6
30	3,150	1	1	3	1	480	480	0	0
31	3,250	1	2	2	1	68	68	1	3
Total		451	785	134	338	7,652	22.6	252	404

Decade of life of tree.	Estimated value of smoothed curve of growth shown in figs. 35 and 36.	Combined corrective factor for age and longevity.																	
		Groups 1–9*	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	Group 19	Group 20	Group 21	Group 22	Group 23	Group 24	Group 25	Groups 26–31
1	27.5	22.5	22.6	22.9	23.3	23.6	24.2	24.7	25.2	25.7	26.1	26.7	27.2	27.7	28.2	28.6	29.0	29.4	29.8
2	26.3	23.6	23.7	24.1	24.4	24.8	25.4	25.9	26.4	26.9	27.4	28.0	28.5	29.0	29.6	30.0	30.4	30.9	31.3
3	25.2	24.6	24.8	25.1	25.5	25.8	26.4	26.9	27.5	28.1	28.5	29.2	29.7	30.3	30.9	31.3	31.7	31.9	32.6
4	24.6	25.2	25.4	25.7	26.1	26.4	27.1	27.6	28.2	28.7	29.2	29.9	30.4	31.0	31.6	32.0	32.5	32.9	33.4
5	24.0	25.8	26.0	26.3	26.7	27.1	27.7	28.3	28.9	29.4	29.9	30.6	31.1	31.7	32.4	32.8	33.2	33.7	34.2
6	23.5	26.4	26.6	26.9	27.3	27.7	28.4	28.9	29.6	30.1	30.6	31.3	31.8	32.5	33.1	33.6	34.0	34.5	35.0
7	23.0	26.9	27.0	27.4	27.9	28.2	28.9	29.5	30.1	30.7	31.2	31.9	32.4	33.1	33.8	34.2	34.7	35.2	35.7
8	22.6	27.4	27.5	27.9	28.4	28.8	29.4	30.0	30.7	31.2	31.8	32.5	33.0	33.7	34.4	34.8	35.3	35.8	36.3
9	22.2	27.9	28.0	28.4	28.9	29.3	30.0	30.6	31.2	31.8	32.3	33.0	33.7	34.3	35.0	35.4	35.9	36.5	37.0
10	21.9	28.3	28.4	28.8	29.3	29.7	30.4	31.0	31.7	32.3	32.8	33.6	34.2	34.8	35.5	36.0	36.4	37.0	37.5
11	21.7	28.6	28.7	29.1	29.6	30.0	30.8	31.4	32.0	32.6	33.2	33.9	34.5	35.2	35.9	36.4	36.8	37.4	37.9
12	21.4	28.9	29.0	29.4	29.9	30.3	31.1	31.7	32.4	33.0	33.6	34.3	34.9	35.6	36.3	36.7	37.2	37.8	38.3
13	21.2	29.2	29.3	29.7	30.2	30.6	31.4	32.0	32.7	33.3	33.9	34.6	35.2	35.9	36.6	37.1	37.6	38.2	38.7
14	21.0	29.5	29.6	30.0	30.6	31.0	31.7	32.3	33.1	33.6	34.2	35.0	35.6	36.3	37.0	37.5	38.0	38.6	39.1
15	20.8	29.8	29.9	30.3	30.9	31.3	32.0	32.6	33.4	34.0	34.6	35.3	36.0	36.7	37.4	37.9	38.4	39.0	39.6
16	20.6	30.1	30.2	30.6	31.2	31.6	32.3	33.0	33.7	34.3	34.9	35.7	36.3	37.0	37.7	38.2	38.8	39.4	39.9
17	20.4	30.4	30.6	30.9	31.5	31.9	32.7	33.3	34.1	34.7	35.3	36.0	36.7	37.4	38.1	38.6	39.2	39.8	40.3
18	20.2	30.7	30.9	31.2	31.8	32.2	33.0	33.6	34.4	35.0	35.6	36.4	37.0	37.8	38.5	39.0	39.6	40.2	40.7
19	20.0	31.0	31.2	31.5	32.1	32.5	33.3	33.9	34.7	35.3	36.0	36.8	37.4	38.2	38.9	39.4	39.9	40.6	41.1
20	19.8	31.3	31.5	31.8	32.4	32.9	33.6	34.3	35.1	35.7	36.3	37.1	37.8	38.6	39.2	39.8	40.3	40.9	41.5
21	19.6	31.6	31.8	32.2	32.7	33.2	34.0	34.6	35.4	36.0	36.7	37.4	38.1	38.9	39.6	40.2	40.7	41.3	41.8
22	19.4	31.9	32.1	32.5	33.0	33.5	34.3	34.9	35.7	36.4	37.0	37.8	38.5	39.2	40.0	40.5	41.1	41.7	42.3
23	19.2	32.3	32.5	32.9	33.5	33.9	34.7	35.4	36.2	36.8	37.5	38.3	39.0	39.7	40.5	41.0	41.6	42.3	42.8
24	19.0	32.6	32.8	33.2	33.8	34.2	35.0	35.7	36.5	37.2	37.8	38.6	39.3	40.2	40.8	41.5	42.0	42.7	43.2
25	18.8	33.0	33.2	33.6	34.2	34.6	35.5	36.2	37.0	37.6	38.3	39.1	39.8	40.6	41.4	41.9	42.5	43.2	43.8
26	18.6	33.3	33.5	33.9	34.5	34.9	35.8	36.5	37.3	38.0	38.6	39.5	40.2	41.0	41.7	42.4	42.9	43.6	44.1
27	18.4	33.7	33.9	34.3	34.9	35.3	36.2	36.9	37.8	38.4	39.1	40.0	40.7	41.5	42.2	42.8	43.4	43.9	44.6
28	18.2	34.1	34.3	34.7	35.3	35.8	36.6	37.3	38.2	38.9	39.6	40.4	41.1	42.0	42.8	43.3	43.9	44.5	45.2
29	18.0	34.4	34.6	35.0	35.6	36.1	37.0	37.7	38.5	39.2	39.9	40.8	41.5	42.4	43.2	43.7	44.3	45.0	45.6
30	17.8	34.8	35.0	35.4	36.0	36.5	37.4	38.1	39.0	39.7	40.3	41.2	42.0	42.8	43.7	44.2	44.8	45.5	46.1
31	17.6	35.2	35.4	35.9	36.4	36.9	37.8	38.6	39.4	40.2	40.8	41.7	42.4	43.3	44.2	44.7	45.3	46.0	46.6
32	17.4	35.6	35.8	36.3	36.8	37.3	38.2	39.0	39.9	40.6	41.3	42.7	42.9	43.8	44.7	45.2	45.8	46.6	47.2
33	17.2	36.0	36.2	36.7	37.2	37.8	38.7	39.4	40.3	41.1	41.8	42.2	43.4	44.3	45.2	45.8	46.4	47.1	47.7
34	17.0	36.5	36.7	37.2	37.7	38.3	39.2	40.0	40.9	41.6	42,4	43.3	44.0	44.9	45.8	46.4	47.0	47.7	48.4
35	16.8	36.9	37.1	37.6	38.2	38.7	39.7	40.5	41.3	42.1	42.8	43.7	44.5	45.5	46.3	47.0	47.5	48.3	48.9
36	16.6	37.4	37.6	38.1	38.7	39.2	40.2	41.0	41.8	42.6	43.4	44.3	45.1	46.0	46.9	47.6	48.2	48.8	49.6
37	16.45	37.7	37.9	38.4	39.0	39.6	40.5	41.3	42.2	43.0	43.7	44.7	45.5	46.4	47.3	48.0	48.6	49.3	49.9
38	16.3	38.0	38.2	38.7	39.3	39.9	40.8	41.7	42.6	43.3	44.1	45.0	45.9	46.8	47.7	48.4	49.0	49.7	50.3
39	16.15	38.4	38.6	39.1	39.8	40.3	41.2	42.1	43.0	43.8	44.6	45.5	46.3	47.2	48.2	48.9	49.4	50.2	50.8
40	16.0	38.8	38.9	39.4	40.1	40.6	41.6	42.4	43.4	44.1	45.0	45.8	46.6	47.6	48.5	49.3	49.9	50.6	51.3
41	15.8	39.2	39.4	39.9	40.6	41.1	42.1	42.9	43.9	44.7	45.5	46.4	47.2	48.2	49.1	49.8	50.5	51.2	51.8
42	15.6	39.7	39.9	40.4	41.1	41.6	42.7	43.5	44.5	45.3	46.0	47.1	47.9	48.8	49.8	50.5	51.1	51.9	52.5
43	15.4	40.2	40.4	40.9	41.6	42.1	43.2	44.0	45.0	45.8	46.6	47.6	48.5	49.5	50.3	51.0	51.7	52.5	53.2
44	15.2	40.8	41.0	41.5	42.2	42.8	43.8	44.7	45.7	46.5	47.3	48.3	49.2	50.2	51.2	51.8	52.5	53.4	54.0
45	15.0	41.3	41.5	42.0	42.7	43.3	44.4	45.2	46.3	47.1	48.0	49.0	49.8	50.9	51.8	52.5	53.2	54.0	54.7
46	14.85	41.7	41.9	42.4	43.1	43.6	44.8	45.7	46.7	47.5	48.4	49.5	50.3	51.3	52.3	53.0	53.7	54.5	55.2
47	14.7	42.2	42.4	42.9	43.6	44.2	45.3	46.2	47.2	48.0	49.0	50.0	51.0	52.0	53.0	53.5	54.3	55.1	55.9
48	14.55	42.6	42.8	43.3	44.0	44.7	45.8	46.6	47.7	48.6	49.4	50.5	51.5	52.5	53.5	54.1	54.9	55.7	56.5
49	14.40	43.0	43.2	43.7	44.5	45.1	46.2	47.1	48.2	49.0	49.9	51.0	51.9	53.0	54.0	54.7	55.4	56.2	57.0
50	14.25	43.5	43.7	44.2	45.0	45.6	46.8	47.7	48.7	49.6	50.5	51.6	52.5	53.5	54.5	55.3	56.0	56.9	57.5
51	14.05	44.2	44.4	45.0	45.7	46.3	47.5	48.4	49.5	50.4	51.2	52.4	53.2	54.3	55.4	56.1	56.8	57.6	58.3
52	13.90	44.6	44.8	45.4	46.1	46.8	47.9	48.9	50.0	50.8	51.7	52.8	53.8	54.9	55.9	56.7	57.5	58.4	59.0
53	13.70	45.2	45.4	46.0	46.7	47.4	48.5	49.5	50.6	51.5	52.4	53.5	54.5	55.6	56.6	57.4	58.2	59.1	59.7
54	13.55	45.7	46.0	46.5	47.2	47.9	49.1	50.0	51.2	52.0	53.0	54.2	55.1	56.2	57.3	58.1	58.8	59.7	60.5
55	13.35	46.4	46.7	47.2	47.9	48.7	49.9	50.8	52.0	52.9	53.8	55.0	56.0	57.1	58.1	59.0	59.7	60.6	61.3
56	13.2	46.9	47.2	47.8	48.6	49.3	50.4	51.4	52.6	53.5	54.4	55.6	56.6	57.7	58.8	59.7	60.4	61.4	62.1
57	13.05	47.5	47.8	48.4	49.2	49.9	51.1	52.0	53.2	54.2	55.2	56.3	57.3	58.5	59.6	60.4	61.2	62.1	62.8
58	12.85	48.2	48.6	49.2	50.0	50.8	52.0	52.9	54.2	55.1	56.0	57.1	58.2	59.3	60.5	61.3	62.0	63.0	63.7
59	12.7	48.8	49.1	49.7	50.5	51.3	52.5	53.5	54.8	55.7	56.7	57.9	59.0	60.0	61.2	62.1	62.9	63.9	64.6
60	12.55	49.4	49.7	50.3	51.2	51.9	53.1	54.1	55.3	56.3	57.3	58.5	59.6	60.8	61.9	62.8	63.6	64.6	65.4
61	12.35	50.2	50.5	51.2	52.0	52.7	53.9	55.0	56.2	57.2	58.2	59.5	60.5	61.7	62.9	63.8	64.6	65.6	66.4
62	12.2	50.8	51.1	51.8	52.6	53.4	54.6	55.7	57.0	58.0	59.0	60.2	61.3	62.5	63.7	54.5	65.4	66.5	67.3
63	12.05	51.5	51.8	52.5	53.3	54.1	55.3	56.4	57.7	58.7	59.8	61.0	62.1	63.4	64.6	65.5	66.3	67.4	68.2
64	11.85	52.3	52.6	53.3	54.1	54.9	56.2	57.3	58.6	59.6	60.7	62.0	63.1	64.4	55.6	66.5	67.3	68.5	69.3
65	11.7	53.0	53.3	54.0	54.8	55.6	57.0	58.1	59.4	60.4	61.5	62.8	64.0	65.3	66.5	67.4	68.3	69.3	70.2
66	11.55	53.7	54.0	54.7	55.6	56.4	57.7	58.8	60.1	61.2	62.2	63.7	64.8	66.1	67.3	68.2	69.1	70.2	71.1
67	11.40	54.4	54.7	55.4	56.3	57.1	58.5	59.5	61.0	62.0	63.1	64.5	65.5	66.9	68.2	69.1	70.0	71.1	72.0
68	11.25	55.1	55.4	56.1	57.0	57.9	59.2	60.4	61.7	62.8	64.0	65.4	66.5	67.8	69.1	70.1	71.0	72.0	73.0
69	11.10	55.8	56.1	56.8	57.7	58.6	60.0	61.2	62.5	63.7	64.7	66.2	67.4	68.6	70.0	71.0	72.0	73.0	74.0
70	10.95	56.6	57.0	57.7	58.6	59.5	61.0	62.0	63.5	64.7	65.7	67.2	68.4	69.7	71.1	72.0	73.0	74.0	75.0
71	10.80	57.3	57.6	58.4	59.3	60.2	61.6	62.8	64.2	65.4	66.5	68.0	69.3	70.5	71.9	72.8	73.9	75.0	75.9
72	10.7	57.9	58.2	59.0	59.9	60.8	62.2	63.4	64.9	66.0	67.1	68.6	70.0	71.3	72.7	73.6	74.7	75.9	76.7
73	10.6	58.5	58.8	59.6	60.5	61.4	62.9	64.1	65.6	66.7	67.9	69.4	70.6	72.0	73.5	74.4	75.5	76.7	77.5
74	10.5	59.1	59.4	60.2	61.1	62.1	63.5	64.8	66.2	67.4	68.5	70.0	71.3	72.7	74.1	75.1	76.2	77.4	78.2
75	10.4	59.7	60.0	60.8	61.6	62.7	64.2	65.4	66.9	68.0	69.3	70.7	72.0	73.5	74.9	75.9	77.0	78.1	79.0
76	10.3	60.3	60.6	61.4	62.4	63.4	64.8	66.1	67.5	68.8	70.0	71.5	72.8	74.2	75.7	76.6	77.8	79.0	79.9
77	10.2	60.9	61.2	62.0	63.0	64.0	65.5	66.7	68.2	69.5	70.6	72.1	73.5	75.0	76.4	77.4	78.5	79.8	80.6
78	10.1	61.5	61.8	62.6	63.7	64.8	66.1	67.4	68.8	70.1	71.4	72.9	74.1	75.6	77.1	78.2	79.2	80.5	81.4
79	10.0	62.1	62.4	63.2	64.3	65.5	66.8	68.0	69.6	70.9	72.0	73.6	75.0	76.4	77.9	79.0	80.0	81.2	82.2
80	9.9	62.7	63.0	63.8	64.9	66.2	67.4	68.6	70.2	71.5	72.7	74.3	75.6	77.1	78.7	79.6	80.8	82.0	83.0

* This column, showing the corrective factor for groups 1–9, is the unaltered factor for age alone, no correction for longevity having seemed necessary in these groups.

Decade of life of tree.	Estimated value of smoothed curve of growth shown in figs. 35 and 36.	Combined corrective factor for age and longevity.																	
		Groups 1-9	Group 10	Group 11	Group 12	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18	Group 19	Group 20	Group 21	Group 22	Group 23	Group 24	Group 25	Groups 26-31
81	9.85	63.0	63.3	64.3	65.3	66.4	67.8	69.0	70.5	71.8	73.1	74.6	76.0	77.5	79.1	80.6	81.2	82.5	83.5
82	9.8	63.3	63.6	64.6	65.6	66.7	68.1	69.4	70.9	72.2	73.5	75.0	76.4	77.9	79.5	81.0	81.6	82.9	83.9
83	9.75	63.7	64.0	65.0	66.0	67.0	68.5	69.8	71.3	72.6	73.9	75.4	76.8	78.3	80.0	81.4	82.0	83.4	84.4
84	9.7	64.0	64.3	65.3	66.3	67.3	68.9	70.2	71.7	73.0	74.3	75.8	77.2	78.7	80.4	81.8	82.4	83.8	84.8
85	9.65	64.3	64.6	65.6	66.6	67.6	69.2	70.6	72.1	73.4	74.7	76.2	77.6	79.1	80.9	82.2	82.8	84.3	85.3
86	9.6	64.7	65.0	66.0	67.0	68.0	69.6	71.0	72.6	73.8	75.1	76.6	78.0	79.5	81.3	82.6	83.2	84.7	85.7
87	9.55	65.0	65.3	66.3	67.4	68.3	69.9	71.4	72.9	74.2	75.5	77.0	78.4	79.9	81.7	83.0	83.6	85.1	86.1
88	9.5	65.3	65.6	66.6	67.7	68.6	70.3	71.7	73.2	74.5	75.8	77.4	78.8	80.3	82.1	83.4	84.0	85.6	86.6
89	9.45	65.7	66.0	67.0	68.1	69.0	70.7	72.0	73.6	74.8	76.2	77.8	79.2	80.7	82.5	83.8	84.4	85.9	86.9
90	9.4	66.0	66.3	67.3	68.4	69.4	71.0	72.3	73.9	75.1	76.6	78.2	79.6	81.1	82.9	84.2	84.8	86.4	87.4
91	9.36	66.3	66.6	67.7	68.7	69.7	71.3	72.6	74.2	75.4	77.0	78.6	79.9	81.4	83.3	84.6	85.2	86.8	87.8
92	9.32	66.6	66.9	67.9	69.0	70.0	71.6	72.9	74.5	75.7	77.4	79.0	80.3	81.8	83.7	85.9	85.6	87.1	88.1
93	9.28	66.9	67.2	68.2	69.3	70.3	71.9	73.2	74.8	76.0	77.8	79.4	80.6	82.1	84.1	85.4	86.0	87.5	88.5
94	9.24	67.2	67.5	68.5	69.6	70.6	72.2	73.5	75.1	76.3	78.2	79.8	81.0	82.5	84.5	85.8	86.4	87.8	88.8
95	9.2	67.4	67.7	68.7	69.8	70.9	72.5	73.8	75.4	76.6	78.5	80.2	81.3	82.8	84.9	86.2	86.8	88.2	89.2
96	9.16	67.7	68.0	69.0	70.1	71.2	72.8	74.1	75.7	76.9	78.8	80.6	81.7	83.2	85.3	86.6	87.2	88.6	89.6
97	9.12	68.0	68.3	69.3	70.4	71.5	73.1	74.4	76.0	77.3	79.1	80.9	82.0	83.5	85.7	87.0	87.6	89.0	90.0
98	9.08	68.3	68.6	69.6	70.7	71.8	73.4	74.7	76.3	77.7	79.4	81.2	82.4	83.9	86.1	87.4	88.0	89.4	90.4
99	9.04	68.6	68.9	69.9	71.0	72.1	73.7	75.0	76.6	78.1	79.7	81.5	82.7	84.2	86.5	87.8	88.2	89.8	90.8
100	9.0	68.9	69.2	70.2	71.3	72.4	74.1	75.4	77.0	78.5	80.0	81.8	83.1	84.6	86.9	88.2	88.8	90.2	91.2
101	8.96	69.2	69.5	70.5	71.6	72.7	74.5	75.7	77.4	78.9	80.4	82.2	83.5	85.0	87.3	88.6	89.2	99.6	91.6
102	8.92	69.6	69.9	70.9	72.0	73.1	74.9	76.0	77.8	79.3	80.8	82.6	83.9	85.5	87.7	89.0	89.6	91.1	92.1
103	8.88	69.9	70.2	71.2	72.4	73.5	75.3	76.4	78.2	79.7	81.2	83.0	84.3	85.9	88.1	89.4	90.0	91.5	92.5
104	8.84	70.3	70.6	71.6	72.8	73.9	75.6	76.8	78.6	80.1	81.6	83.4	84.7	86.4	88.5	89.8	90.4	92.0	93.0
105	8.8	70.6	79.9	72.0	73.2	74.2	76.0	77.2	79.0	80.5	82.0	83.8	85.1	86.8	88.9	90.2	90.8	92.4	93.4
106	8.76	71.0	71.3	72.4	73.6	74.6	76.4	77.6	79.4	80.9	82.4	84.2	85.5	87.3	89.3	90.6	91.1	92.9	93.9
107	8.72	71.3	71.7	72.7	73.9	74.9	76.7	78.0	79.8	81.3	82.8	84.6	85.9	87.7	89.7	91.0	91.4	93.3	94.3
108	8.68	71.6	72.0	73.0	74.2	75.2	77.0	78.4	80.2	81.7	83.2	85.0	86.3	88.2	90.1	91.4	91.7	93.8	94.8
109	8.64	71.9	72.3	73.4	74.6	75.5	77.3	78.8	80.6	82.1	83.5	85.3	86.7	88.6	90.5	91.8	92.0	94.2	95.2
110	8.6	72.3	72.7	73.7	74.9	75.9	77.8	79.1	81.0	82.5	83.9	85.7	87.1	89.1	90.9	92.2	92.3	94.7	95.7
111	8.57	72.6	73.0	74.0	75.2	76.2	78.1	79.4	81.3	82.8	84.2	86.0	87.4	89.5	91.2	92.5	92.7	95.0	96.0
112	8.54	72.8	73.2	74.2	75.5	76.5	78.4	79.7	81.6	83.1	84.5	86.3	87.7	89.8	91.5	92.9	93.1	95.3	96.3
113	8.51	73.1	73.5	74.5	75.8	76.8	78.7	80.0	81.9	83.4	84.8	86.6	88.0	90.1	91.8	93.2	93.5	95.6	96.6
114	8.49	73.3	73.7	74.7	76.0	77.1	79.0	80.3	82.2	83.7	85.1	86.9	88.3	90.4	92.1	93.6	93.9	95.9	96.9
115	8.46	73.5	73.9	74.9	76.2	77.4	79.2	80.6	82.5	83.9	85.4	87.2	88.6	90.7	92.4	93.9	94.3	96.2	97.2
116	8.43	73.8	74.2	75.2	76.5	77.7	79.5	80.9	82.8	84.2	85.7	87.5	88.9	91.0	92.7	94.3	94.7	96.5	97.5
117	8.4	74.0	74.4	75.5	76.7	77.9	79.7	81.2	83.1	84.4	85.9	87.8	89.2	91.3	93.0	94.6	95.1	96.8	97.8
118	8.37	74.2	74.6	75.7	76.9	78.1	80.0	81.4	83.3	84.6	86.1	88.1	89.5	91.6	93.3	95.0	95.5	97.1	98.1
119	8.34	74.4	74.8	75.9	77.1	78.3	80.2	81.6	83.5	84.8	86.3	88.3	89.8	91.9	93.6	95.3	95.9	97.4	98.4
120	8.31	74.7	75.1	76.2	77.4	78.5	80.4	81.8	83.7	85.1	86.6	88.6	90.1	92.2	93.9	95.6	96.3	97.7	98.8
121	8.28	74.9	75.3	76.4	77.7	78.7	80.7	82.1	84.0	85.3	86.9	88.9	90.4	92.5	94.2	95.9	96.6	98.0	99.0
122	8.26	75.1	75.5	76.6	78.0	78.9	80.9	82.4	84.3	85.6	87.2	89.2	90.7	92.8	94.5	96.2	96.9	98.2	99.2
123	8.24	75.3	75.7	76.8	78.2	79.1	81.1	82.6	84.5	85.8	87.5	89.5	91.0	93.0	94.8	96.5	97.2	98.5	99.5
124	8.22	75.5	75.9	77.0	78.4	79.3	81.3	82.8	84.7	86.1	87.8	89.8	91.3	93.2	95.1	96.8	97.5	98.7	99.7
125	8.2	75.7	76.1	77.2	78.6	79.5	81.5	83.0	84.9	86.3	88.0	90.0	91.5	93.4	95.4	97.1	97.8	99.0	100.0
126	8.18	75.9	76.3	77.4	78.8	79.7	81.7	83.2	85.1	86.6	88.2	90.2	91.7	93.6	95.6	97.4	98.0	99.2	100.2
127	8.16	76.1	76.5	77.6	79.0	79.9	81.9	83.4	85.3	86.8	88.4	90.4	91.9	93.8	95.8	97.6	98.2	99.5	100.5
128	8.14	76.3	76.7	77.8	79.2	80.1	82.1	83.6	85.5	87.1	88.6	90.6	92.1	94.0	96.0	97.8	98.4	99.7	100.7
129	8.12	76.5	76.9	78.0	79.4	80.3	82.3	83.8	85.7	87.3	88.8	90.8	92.3	94.2	96.2	98.0	98.6	100.0	101.0
130	8.1	76.7	77.1	78.2	79.5	80.5	82.5	84.0	85.9	87.5	89.0	91.0	92.5	94.4	96.4	98.2	98.8	100.2	101.2
131	8.09	76.8	....	78.3	79.6	80.6	82.6	84.1	86.1	87.6	89.1	91.1	92.7	94.6	96.6	98.4	99.0	100.3	101.3
132	8.08	76.9	....	78.4	79.7	80.7	82.7	84.2	86.3	87.7	89.2	91.2	92.8	94.7	96.7	98.5	99.1	100.5	101.5
133	8.07	77.0	....	78.5	79.8	80.8	82.8	84.3	86.4	87.8	89.3	91.3	92.9	94.8	96.9	98.6	99.3	100.6	101.6
134	8.06	77.1	....	78.6	79.9	80.9	82.9	84.4	86.5	87.9	89.4	91.4	93.0	94.9	97.0	98.7	99.4	100.8	101.8
135	8.05	77.2	....	78.7	80.0	81.0	83.0	84.5	86.6	88.0	89.5	91.5	93.1	95.0	97.1	98.8	99.6	100.9	101.9
136	8.04	77.3	....	78.8	80.1	81.1	83.1	84.6	86.7	88.1	89.6	91.6	93.2	95.1	97.2	98.9	99.7	101.0	102.0
137	8.03	77.4	....	78.9	80.2	81.2	83.2	84.7	86.8	88.2	89.7	91.7	93.3	95.2	97.3	99.0	99.9	101.2	102.2
138	8.02	77.5	....	79.0	80.3	81.3	83.3	84.8	86.9	88.3	89.8	91.8	93.4	95.3	97.4	89.1	100.0	101.3	102.3
139	8.01	77.5	....	79.1	80.4	81.4	83.4	84.9	87.0	88.4	89.9	91.9	93.5	95.4	97.5	99.2	100.2	101.5	102.5
140	8.0	77.6	....	79.2	80.5	81.5	83.5	85.0	87.1	88.5	90.0	92.0	93.6	95.5	97.6	99.3	100.3	101.7	102.7
141	7.99	77.7	....	......	80.6	81.6	83.6	85.1	87.2	88.7	90.2	92.2	93.7	95.6	97.8	99.4	100.5	101.8	102.8
142	7.98	77.8	....	......	80.7	81.7	83.7	85.2	87.3	88.8	90.3	92.4	93.9	95.7	97.9	99.5	109.6	102.0	103.0
143	7.97	77.9	....	......	80.8	81.8	82.8	85.3	87.4	88.9	90.4	92.5	94.0	95.8	98.1	99.6	100.8	102.1	103.1
144	7.96	78.0	....	......	80.9	81.9	83.9	85.4	87.5	89.0	90.5	92.6	94.2	95.9	98.2	99.7	100.9	102.3	103.3
145	7.95	78.1	....	......	81.0	82.0	84.0	85.5	87.6	89.1	90.6	92.7	94.3	96.0	98.3	99.8	101.1	102.4	103.4
146	7.94	78.2	....	......	81.1	82.1	84.1	85.6	87.7	89.2	90.7	92.8	94.4	96.1	98.4	99.9	101.2	102.6	103.6
147	7.93	78.3	....	......	81.2	82.2	84.2	85.7	87.8	89.3	90.8	92.9	94.5	96.2	98.5	100.0	101.4	102.7	103.7
148	7.92	78.4	....	......	81.3	82.3	84.3	85.8	87.9	89.4	90.9	93.0	94.6	96.3	98.6	100.1	101.5	102.8	103.8
149	7.91	78.5	....	......	81.4	82.4	84.5	85.9	88.0	89.5	91.0	93.1	94.7	96.4	98.7	100.2	101.7	102.9	103.9
150	7.9	78.6	....	......	81.5	82.5	84.5	86.0	88.1	89.6	91.1	93.2	94.8	96.5	98.8	100.3	101.8	103.0	104.0
151	7.89	78.7	....	......	......	82.6	84.6	86.1	88.2	89.8	91.3	93.3	94.9	96.7	99.0	100.5	101.9	103.1	104.1
152	7.88	78.8	....	......	......	82.7	84.7	86.2	88.3	90.0	91.5	93.4	95.1	96.8	99.1	100.6	102.0	103.3	104.3
153	7.87	78.9	....	......	......	82.8	84.8	86.3	88.4	90.1	91.7	93.5	95.2	97.0	99.3	100.7	102.1	103.4	104.4
154	7.86	79.0	....	......	......	82.9	84.9	86.4	83.5	90.2	91.8	93.6	95.4	97.1	99.4	100.8	102.2	103.6	104.6
155	7.85	79.1	....	......	......	83.0	85.0	86.5	88.6	90.3	91.9	93.7	95.5	97.3	99.5	100.9	102.3	103.7	104.7
156	7.84	79.2	....	......	......	83.1	85.1	86.6	88.7	90.4	92.0	93.8	95.6	97.4	99.6	101.0	102.4	103.8	104.8
157	7.83	79.3	....	......	......	83.2	85.2	86.7	88.8	90.5	92.1	93.9	95.7	97.6	99.7	101.1	102.5	103.9	104.9
158	7.82	79.4	....	......	......	83.3	85.3	86.8	88.9	90.6	92.2	94.0	95.8	97.7	99.8	101.2	102.6	104.0	105.0
159	7.81	79.5	....	......	......	83.4	85.4	86.9	89.0	90.7	92.3	94.1	95.9	97.8	99.9	101.3	102.7	104.1	105.1
160	7.8	79.6	....	......	......	83.5	85.5	87.0	89.1	90.8	92.4	94.2	96.0	97.9	100.0	101.4	102.8	104.2	105.2

Decade of life of tree.	Estimated value of smoothed curve of growth shown in figs. 35 and 36	Combined corrective factor for age and longevity. Groups 1–9	Group 15	Group 16	Group 17	Group 18	Group 19	Group 20	Group 21	Group 22	Group 23	Group 24	Group 25	Groups 26–31
161	7.79	79.7	87.1	89.3	91.2	92.6	94.3	96.1	98.1	100.2	101.6	103.0	104.3	105.3
162	7.78	79.8	87.2	89.5	91.3	92.7	94.4	96.2	98.2	100.3	101.7	103.1	104.5	105.5
163	7.77	79.9	87.3	89.6	91.4	92.8	94.5	96.3	98.4	100.5	101.9	103.3	104.6	105.6
164	7.76	80.0	87.4	89.7	91.5	92.9	94.6	96.5	98.5	100.6	102.0	103.4	104.8	105.8
165	7.75	80.1	87.5	89.8	91.6	93.0	94.7	96.6	98.7	100.7	102.2	103.5	104.9	105.9
166	7.74	80.2	87.6	89.9	91.7	93.1	94.8	96.7	98.8	100.8	102.3	103.6	105.0	106.0
167	7.73	80.3	87.7	90.0	91.8	93.2	94.9	96.8	98.9	100.9	102.4	103.7	105.1	106.1
168	7.72	80.4	87.8	90.1	91.9	93.3	95.0	96.9	99.0	101.0	102.5	103.8	105.3	106.3
169	7.71	80.5	87.9	90.2	92.0	93.4	95.1	97.0	99.1	101.1	102.6	103.9	105.4	106.4
170	7.7	80.6	88.0	90.3	92.1	93.5	95.2	97.1	99.2	101.2	102.7	104.0	105.5	106.5
171	7.69	80.7	.....	90.4	92.3	93.7	95.3	97.3	99.4	101.4	102.9	104.2	105.6	106.6
172	7.68	80.8	.....	90.5	92.4	93.9	95.4	97.4	99.5	101.5	103.0	104.3	105.7	106.7
173	7.67	80.9	.....	90.6	92.5	94.0	95.5	97.5	99.6	101.7	103.2	104.5	105.9	106.9
174	7.66	81.0	.....	90.7	92.6	94.1	95.6	97.7	99.7	101.8	103.3	104.6	106.0	107.0
175	7.65	81.2	.....	90.8	92.7	94.2	95.7	97.8	99.8	102.0	103.5	104.8	106.2	107.2
176	7.64	81.3	.....	90.9	92.8	94.3	95.8	98.0	99.9	102.1	103.6	104.9	106.3	107.3
177	7.63	81.4	.....	91.0	92.9	94.4	95.9	98.1	100.0	102.3	103.7	105.0	106.5	107.5
178	7.62	81.5	.....	91.1	93.0	94.5	96.0	98.3	100.1	102.5	103.8	105.1	106.6	107.6
179	7.61	81.6	.....	91.2	93.1	94.6	96.1	98.4	100.2	102.6	103.9	105.2	106.8	107.8
180	7.6	81.7	.....	91.3	93.2	94.7	96.2	98.5	100.3	102.7	104.0	105.3	106.9	107.9
181	7.59	81.8	.....	.....	93.4	94.9	96.4	98.7	100.5	102.9	104.2	105.5	107.0	108.0
182	7.58	81.9	.....	.....	93.6	95.1	96.6	98.8	100.6	103.0	104.3	105.6	107.1	108.1
183	7.57	82.0	.....	.....	93.5	95.3	96.8	99.0	100.8	103.2	104.5	105.8	107.3	108.3
184	7.56	82.1	.....	.....	93.6	95.4	97.0	99.1	100.9	103.3	104.6	105.9	107.4	108.4
185	7.55	82.2	.....	.....	93.7	95.5	97.2	99.3	101.0	103.5	104.8	106.1	107.6	108.6
186	7.54	82.3	.....	.....	93.8	95.6	97.3	99.4	101.2	103.6	104.9	106.2	107.7	108.7
187	7.53	82.4	.....	.....	93.9	95.7	97.4	99.6	101.3	103.7	105.1	106.4	107.9	108.9
188	7.52	82.5	.....	.....	94.0	95.8	97.5	99.7	101.5	103.8	105.2	106.5	108.0	109.0
189	7.51	82.6	.....	.....	94.2	95.9	97.6	99.8	101.6	103.9	105.4	106.6	108.2	109.2
190	7.5	82.8	.....	.....	94.4	96.0	97.7	99.9	101.8	104.0	105.5	106.7	108.3	109.3
191	7.49	82.9	.....	.....	94.5	96.2	97.9	100.1	101.9	104.2	105.7	106.9	108.4	109.4
192	7.48	83.0	.....	.....	94.6	96.4	98.1	100.2	102.1	104.3	105.8	107.0	108.5	109.5
193	7.47	33.1	.....	.....	94.7	96.6	98.3	100.4	102.3	104.5	106.0	107.2	108.7	109.7
194	7.46	83.2	.....	.....	94.8	96.7	98.4	100.5	102.4	101.6	106.1	107.3	108.8	109.8
195	7.45	83.3	.....	.....	94.9	96.8	98.5	100.6	102.6	104.8	106.3	107.5	109.0	110.0
196	7.44	83.4	.....	.....	95.0	96.9	98.6	100.7	102.7	104.9	106.4	107.6	109.1	110.1
197	7.43	83.5	.....	.....	95.1	97.0	98.7	100.8	102.9	105.1	106.6	107.8	109.3	110.3
198	7.42	83.6	.....	.....	95.2	97.1	98.8	100.9	103.0	105.3	106.7	107.9	109.4	110.4
199	7.41	83.7	.....	.....	95.3	97.3	98.9	101.0	103.2	105.4	106.9	108.0	109.6	110.6
200	7.4	83.9	.....	.....	95.4	97.4	99.0	101.1	103.3	105.5	107.0	108.1	109.7	110.7
201	7.39	84.0	.....	.....	.....	97.6	99.2	101.3	103.5	105.7	107.2	108.3	109.9	110.9
202	7.38	84.1	.....	.....	.....	97.8	99.4	101.4	103.6	105.8	107.3	108.4	110.0	111.0
203	7.37	84.2	.....	.....	.....	98.0	99.6	101.6	103.8	106.0	107.5	108.6	110.2	111.2
204	7.36	84.3	.....	.....	.....	98.1	99.7	101.7	103.9	106.1	107.6	108.7	110.3	111.3
205	7.35	84.5	.....	.....	.....	98.2	99.8	101.9	104.1	106.3	107.8	108.9	110.5	111.5
206	7.34	84.6	.....	.....	.....	98.3	99.9	102.0	104.2	106.4	107.9	109.0	110.6	111.6
207	7.33	84.7	.....	.....	.....	98.4	100.0	102.2	104.4	106.6	108.1	109.2	110.8	111.8
208	7.32	84.8	.....	.....	.....	98.5	100.1	102.3	104.5	106.7	108.2	109.3	110.9	111.9
209	7.31	84.9	.....	.....	.....	98.6	100.2	102.4	104.7	106.8	108.4	109.5	111.1	112.1
210	7.3	85.1	.....	.....	.....	98.7	100.3	102.5	104.8	106.9	108.5	109.6	111.3	112.3
211	7.29	85.2	.....	.....	.....	.....	100.5	102.7	104.9	107.1	108.7	109.8	111.4	112.4
212	7.28	85.3	.....	.....	.....	.....	100.7	102.8	105.1	107.2	108.8	109.9	111.5	112.5
213	7.27	85.4	.....	.....	.....	.....	100.9	103.0	105.2	107.4	109.0	110.1	111.7	112.7
214	7.26	85.5	.....	.....	.....	.....	101.1	103.1	105.4	107.5	109.1	110.2	111.8	112.8
215	7.25	85.6	.....	.....	.....	.....	101.3	103.3	105.5	107.7	109.3	110.4	112.0	113.0
216	7.24	85.7	.....	.....	.....	.....	101.5	103.4	105.6	107.8	109.4	110.5	112.1	113.1
217	7.23	85.8	.....	.....	.....	.....	101.7	103.6	105.7	108.0	109.6	110.7	112.3	113.3
218	7.22	85.9	.....	.....	.....	.....	101.9	103.7	105.8	108.1	109.7	110.8	112.5	113.5
219	7.21	86.0	.....	.....	.....	.....	102.1	103.8	105.9	108.3	109.9	111.0	112.7	113.7
220	7.2	86.2	.....	.....	.....	.....	102.3	103.9	106.0	108.4	110.0	111.1	112.8	113.8
221	7.19	86.3	.....	.....	.....	.....	.....	104.1	106.1	108.6	110.2	111.3	113.0	114.0
222	7.18	86.4	.....	.....	.....	.....	.....	104.2	106.3	108.7	110.3	111.4	113.1	114.1
223	7.17	86.5	.....	.....	.....	.....	.....	104.4	106.4	108.9	110.5	111.6	113.3	114.3
224	7.16	86.6	.....	.....	.....	.....	.....	104.5	106.6	109.0	110.6	111.7	113.4	114.4
225	7.15	86.8	.....	.....	.....	.....	.....	104.7	106.7	109.2	110.8	111.9	113.6	114.6
226	7.14	86.9	.....	.....	.....	.....	.....	104.8	106.9	109.3	110.9	112.0	113.7	114.7
227	7.13	87.0	.....	.....	.....	.....	.....	104.9	107.0	109.5	111.1	112.2	113.9	114.9
228	7.12	87.1	.....	.....	.....	.....	.....	105.0	107.2	109.6	111.2	112.3	114.0	115.0
229	7.11	87.2	.....	.....	.....	.....	.....	105.1	107.4	109.8	111.4	112.5	114.2	115.2
230	7.1	87.4	.....	.....	.....	.....	.....	105.2	107.5	109.9	111.5	112.6	114.3	115.3
231	7.09	87.6	.....	.....	.....	.....	.....	.....	107.7	110.1	111.7	112.8	114.5	115.5
232	7.08	87.7	.....	.....	.....	.....	.....	.....	107.8	110.2	111.8	112.9	114.6	115.6
233	7.07	87.8	.....	.....	.....	.....	.....	.....	108.0	110.4	112.0	113.1	114.8	115.8
234	7.06	87.9	.....	.....	.....	.....	.....	.....	108.1	110.5	112.2	113.2	114.9	116.0
235	7.05	88.0	.....	.....	.....	.....	.....	.....	108.3	110.6	112.3	113.3	115.0	116.1
236	7.04	88.2	.....	.....	.....	.....	.....	.....	108.4	110.8	112.5	113.5	115.2	116.3
237	7.03	88.3	.....	.....	.....	.....	.....	.....	108.6	110.9	112.7	113.7	115.4	116.5
238	7.02	88.4	.....	.....	.....	.....	.....	.....	108.7	111.1	112.8	113.9	115.6	116.7
239	7.01	88.5	.....	.....	.....	.....	.....	.....	108.9	111.2	113.0	114.1	115.8	116.9
240	7.0	88.7	.....	.....	.....	.....	.....	.....	109.0	111.3	113.2	114.3	116.0	117.1

Decade of life of tree.	Estimated value of smoothed curve of growth shown in figs. 35 and 36	Combined corrective factor for age and longevity. Groups 1–9	Group 22	Group 23	Group 24	Group 25	Groups 26–31
241	6.99	88.8	111.5	113.4	114.5	116.2	117.2
242	6.98	88.9	111.6	113.5	114.6	116.3	117.3
243	6.97	89.1	111.7	113.7	114.8	116.5	117.5
244	6.96	89.2	111.9	113.8	114.9	116.6	117.6
245	6.95	89.3	112.0	114.0	115.1	116.8	117.8
246	6.94	89.5	112.2	114.1	115.2	116.9	117.9
247	6.93	89.6	112.3	114.3	115.4	117.1	118.1
248	6.92	89.7	112.5	114.4	115.6	117.3	118.3
249	6.91	89.8	112.6	114.6	115.8	117.5	118.5
250	6.9	90.0	112.8	114.7	116.0	117.7	118.7
251	6.89	90.1	.....	114.9	116.2	117.9	118.9
252	6.88	90.2	.....	115.0	116.3	118.0	119.0
253	6.87	90.4	.....	115.2	116.5	118.2	119.2
254	6.86	90.5	.....	115.3	116.6	118.3	119.3
255	6.85	90.6	.....	115.5	116.8	118.5	119.5
256	6.84	90.8	.....	115.6	117.0	118.7	119.7
257	6.83	90.9	.....	115.8	117.2	118.9	119.9
258	6.82	91.0	.....	115.9	117.4	119.1	120.1
259	6.81	91.1	.....	116.1	117.6	119.3	120.3
260	6.8	91.3	.....	116.2	117.8	119.5	120.5
261	6.79	91.4	.....	.....	117.9	119.6	120.6
262	6.78	91.6	.....	.....	118.1	119.8	120.8
263	6.77	91.7	.....	.....	118.3	120.0	121.0
264	6.76	91.9	.....	.....	118.5	120.2	121.2
265	6.75	92.0	.....	.....	118.7	120.4	121.4
266	6.74	92.2	.....	.....	118.9	120.6	121.6
267	6.73	92.3	.....	.....	119.1	120.8	121.8
268	6.72	92.5	.....	.....	119.3	121.0	122.0
269	6.71	92.6	.....	.....	119.5	121.2	122.2
270	6.7	92.8	.....	.....	119.7	121.4	122.4
271	6.69	92.9	.....	.....	.....	121.6	122.6
272	6.68	93.0	.....	.....	.....	121.8	122.8
273	6.67	93.2	.....	.....	.....	122.0	123.0
274	6.66	93.3	.....	.....	.....	122.2	123.2
275	6.65	93.4	.....	.....	.....	122.4	123.4
276	6.64	93.6	.....	.....	.....	122.6	123.6
277	6.63	93.7	.....	.....	.....	122.8	123.8
278	6.62	93.8	.....	.....	.....	123.0	124.0
279	6.61	93.9	.....	.....	.....	123.2	124.2
280	6.6	94.1	.....	.....	.....	123.4	124.4
281	6.59	94.2	.....	.....	.....	.....	124.6
282	6.58	94.4	.....	.....	.....	.....	124.8
283	6.57	94.5	.....	.....	.....	.....	125.0
284	6.56	94.7	.....	.....	.....	.....	125.2
285	6.55	94.8	.....	.....	.....	.....	125.4
286	6.54	95.0	.....	.....	.....	.....	125.6
287	6.53	95.1	.....	.....	.....	.....	125.8
288	6.52	95.3	.....	.....	.....	.....	126.0
289	6.51	95.4	.....	.....	.....	.....	126.2
290	6.5	95.6	.....	.....	.....	.....	126.4
291	6.49	95.8	.....	.....	.....	.....	126.6
292	6.48	95.9	.....	.....	.....	.....	126.8
293	6.47	96.1	.....	.....	.....	.....	127.0
294	6.46	96.3	.....	.....	.....	.....	127.2
295	6.45	96.4	.....	.....	.....	.....	127.4
296	6.44	96.6	.....	.....	.....	.....	127.6
297	6.43	96.7	.....	.....	.....	.....	127.8
298	6.42	96.9	.....	.....	.....	.....	128.0
299	6.41	97.0	.....	.....	.....	.....	128.2
300	6.4	97.2	.....	.....	.....	.....	128.4
301	6.39	97.3	.....	.....	.....	.....	128.6
302	6.38	97.4	.....	.....	.....	.....	128.8
303	6.37	97.6	.....	.....	.....	.....	129.0
304	6.36	97.7	.....	.....	.....	.....	129.2
305	6.35	97.8	.....	.....	.....	.....	129.4
306	6.34	98.0	.....	.....	.....	.....	129.6
307	6.33	98.1	.....	.....	.....	.....	129.8
308	6.32	98.2	.....	.....	.....	.....	130.0
309	6.31	98.3	.....	.....	.....	.....	130.2
310	6.3	98.5	.....	.....	.....	.....	130.4
311	6.29	98.6	.....	.....	.....	.....	130.6
312	6.28	98.8	.....	.....	.....	.....	130.8
313	6.27	98.9	.....	.....	.....	.....	131.0
314	6.26	99.1	.....	.....	.....	.....	131.2
315	6.25	99.2	.....	.....	.....	.....	131.4
316	6.24	99.4	.....	.....	.....	.....	131.6
317	6.23	99.5	.....	.....	.....	.....	131.8
318	6.22	99.7	.....	.....	.....	.....	132.0
319	6.21	99.8	.....	.....	.....	.....	132.2
320	6.2	100.0	.....	.....	.....	.....	132.4

Group. (See note at end of table, page 322.)	1901-10 A.D.	1891-1900	1881-90	1871-80	1861-70	1851-60	1841-50	1831-40	1821-30	1811-20	1801-10	1791-1800	1781-90	1771-80	1761-70	1751-60	1741-50	1731-40	1721-30	1711-20	1701-10
1. Total growth	77.5	138.0	177.5	183.5	153.0	173.0	141.0	188.0	177.0	136.5	176.0	160.0	178.0	143.5	124.0	127.5	133.5	118.5	124.5	151.0	161.5
No. of measurements	3	6	7																		
Corrected growth	25.8	45.5	57.9	59.2	58.3	54.6	44.1	58.3	54.3	41.5	53.0	47.7	52.5	41.8	35.8	36.4	37.8	33.0	34.1	40.7	43.5
2. Total growth	38.0	128.0	134.5	146.5	160.5	160.0	134.0	125.5	116.0	131.0	115.5	114.0	135.0	138.5	167.5	152.0	170.0	129.0	131.5	153.5	121.0
No. of measurements	2	7	8								8										8
Corrected growth	14.2	47.2	49.0	52.7	57.9	56.3	46.7	43.1	39.5	44.2	38.4	37.6	44.0	44.7	53.5	48.0	40.7	40.0	40.4	46.6	36.4
3. Total growth	92.0	237.5	261.5	266.0	283.5	295.5	267.5	279.0	256.5	308.0	353.5	335.0	323.0	334.0	334.0	366.0	408.5	414.5	406.0	400.5	407.5
No. of measurements	6	13	15	15																	
Corrected growth	37.6	95.4	103.8	104.2	110.0	113.5	101.8	105.1	96.0	113.6	128.9	120.5	115.0	117.2	116.1	125.8	139.3	139.6	135.0	135.0	132.8
4. Total growth	23.5	163.0	580.0	742.0	694.5	687.5	703.5	714.0	673.5	694.0	769.5	754.0	737.0	729.0	780.0	781.0	825.0	831.0	876.5	806.5	851.0
No. of measurements	2	10	48	63																	
Corrected growth	11.2	76.5	269.0	339.0	314.0	306.0	311.0	311.0	389.0	296.0	324.0	314.0	305.0	298.0	313.0	310.0	324.0	323.0	337.0	307.0	324.0
5. Total growth	60.0	203.0	234.5	241.0	262.5	269.0	269.0	268.0	282.5	285.0	287.5	288.0	304.0	331.5	345.5	353.5	360.0	363.0	381.0	365.5	375.0
No. of measurements	8	15	20	21	21																
Corrected growth	32.6	109.0	124.5	126.0	135.5	135.3	135.0	132.5	138.0	137.5	136.5	135.0	141.0	151.0	156.0	157.5	159.0	158.0	163.5	155.5	158.0
6. Total growth	17.5	60.5	92.0	92.0	89.0	92.5	99.0	89.5	91.0	95.0	102.0	101.0	103.5	99.0	109.0	108.5	127.5	141.0	129.5	138.0	115.5
No. of measurements	2	7	10	10																	
Corrected growth	10.7	36.5	55.0	54.3	52.1	53.5	56.8	50.6	50.8	52.3	55.5	54.2	55.0	51.8	56.4	55.2	63.9	69.6	63.2	66.4	51.9
7. Total growth		44.5	152.5	161.5	160.5	163.5	157.0	149.5	148.0	155.0	173.0	170.0	167.0	180.5	155.0	170.5	188.5	176.0	199.0	188.5	172.5
No. of measurements		4	15	17	17																
Corrected growth		29.0	98.5	103.8	102.7	104.3	99.5	94.3	92.6	96.3	106.4	103.4	100.8	107.8	88.6	99.9	109.0	101.0	112.6	105.2	95.1
8. Total growth	34.0	148.5	304.5	285.5	292.5	264.0	279.0	288.0	291.5	310.5	282.0	297.0	283.0	286.5	283.5	275.5	281.0	299.0	322.5	311.0	286.0
No. of measurements	4	13	25	26	26																
Corrected growth	23.3	101.5	207.0	193.3	197.0	177.5	186.8	192.0	193.5	205.0	185.3	194.0	184.0	185.0	182.5	176.5	179.3	189.5	203.2	195.0	177.7
9. Total growth		359.5	441.0	423.5	474.0	450.0	424.5	403.0	412.0	418.0	443.5	418.5	390.5	421.5	416.0	471.0	481.0	472.0	449.0	455.5	466.0
No. of measurements		28	41	41	42																
Corrected growth		254.0	309.0	296.0	329.0	311.5	292.5	276.5	281.0	285.0	300.5	282.5	262.5	282.0	278.0	312.0	317.5	310.0	293.5	296.0	301.0
10. Total growth	30.0	347.0	449.0	437.0	429.0	418.5	395.5	410.5	384.0	431.0	438.5	431.5	419.0	413.5	430.5	401.5	409.5	448.0	444.0	427.5	407.0
No. of measurements	3	34	42																		
Corrected growth	22.2	330.5	330.5	322.0	314.0	306.0	288.0	297.0	287.0	309.0	313.0	306.0	296.0	290.0	301.0	379.0	383.0	308.0	302.0	292.0	277.0
11. Total growth		456.5	691.5	668.0	641.0	677.5	715.5	719.0	712.0	747.0	733.5	730.0	713.5	782.5	743.0	773.5	786.5	755.5	726.5	768.5	708.5
No. of measurements		51	72	74	74	75	75														
Corrected growth		353.0	532.0	513.0	491.0	517.0	545.0	546.0	539.0	565.0	552.0	547.0	533.0	583.0	552.0	572.0	580.0	555.0	531.0	558.0	513.0
12. Total growth	40.5	425.0	612.5	702.0	651.0	702.0	612.0	623.0	612.5	632.0	630.5	601.0	593.5	593.5	595.5	655.0	680.0	651.5	616.0	586.5	582.5
No. of measurements	4	43	54	59																	
Corrected growth	32.4	340.0	488.0	558.0	518.0	557.0	485.0	493.0	484.0	497.0	496.0	472.0	464.0	463.0	463.0	507.0	524.0	503.0	473.0	448.0	443.0
13. Total growth	77.5	363.0	452.0	421.5	400.0	431.0	430.0	406.0	436.0	445.0	503.0	431.5	400.5	431.0	407.5	428.5	429.0	432.5	417.5	421.0	425.5
No. of measurements	5	37	49	49																	
Corrected growth	63.6	298.5	370.0	345.0	327.0	352.0	351.0	331.0	354.0	362.0	408.0	350.0	324.0	319.0	329.0	346.0	346.0	348.0	335.0	337.0	340.0
14. Total growth	48.0	393.5	518.5	492.0	484.5	496.0	450.5	476.5	472.5	481.5	504.5	476.5	483.0	473.0	462.5	490.0	496.0	532.0	498.0	478.5	467.5
No. of measurements	3	39	51	51																	
Corrected growth	40.9	335.0	432.0	418.0	410.0	411.0	381.0	402.0	399.0	407.0	425.0	401.0	406.0	396.0	399.0	410.0	415.0	444.0	415.0	399.0	388.0
15. Total growth		334.5	385.5	392.0	363.5	369.5	369.5	375.5	387.5	394.5	382.0	376.5	385.0	401.5	395.0	387.5	400.5	391.5	365.0	370.0	386.5
No. of measurements		38	47	47																	
Corrected growth		293.0	337.0	342.0	316.5	321.0	321.0	326.0	336.0	342.0	330.5	325.0	332.5	346.5	340.0	334.0	344.0	336.0	313.0	317.0	331.0
16. Total growth		238.0	311.5	288.5	252.5	249.5	233.0	217.5	240.5	246.0	259.5	271.5	280.0	256.0	233.0	240.5	232.5	239.0	231.5	237.5	236.0
No. of measurements		23	33	33																	
Corrected growth		216.0	282.0	261.0	228.0	225.0	210.0	223.0	216.0	221.0	232.5	243.0	250.5	229.0	207.0	214.0	207.0	212.0	205.5	210.5	204.0
17. Total growth		250.0	304.5	334.0	342.0	337.0	358.0	332.0	330.5	351.0	347.5	337.5	310.0	339.0	310.5	337.0	360.0	336.5	363.5	351.5	354.0
No. of measurements		36	42	47																	
Corrected growth		234.0	285.0	311.0	319.0	314.0	334.0	308.5	307.0	325.5	322.0	307.0	287.0	308.0	287.0	306.0	330.5	305.5	334.0	321.4	324.0
18. Total growth		222.0	259.0	257.0	274.0	246.0	252.5	250.5	259.0	258.5	269.5	244.5	241.0	260.5	244.5	255.0	271.5	287.5	279.5	241.0	245.0
No. of measurements		24	27	30	30																
Corrected growth		212.5	249.0	247.0	264.0	236.0	242.0	240.5	248.0	247.5	257.0	232.0	229.0	247.5	232.0	242.0	257.0	272.0	256.0	229.0	230.0
19. Total growth		140.5	164.0	184.0	177.0	192.5	193.5	195.0	187.5	196.0	201.5	210.5	198.5	201.0	199.0	197.5	201.5	199.5	203.5	209.0	217.5
No. of measurements		19	25	25																	
Corrected growth		140.0	163.5	183.0	176.0	191.0	192.0	193.0	185.0	193.0	201.0	207.0	191.5	197.0	194.5	193.0	196.5	194.5	198.0	203.0	211.5
20. Total growth	35.0	357.5	433.5	395.5	397.0	406.0	417.0	432.0	397.5	425.5	412.5	425.5	399.5	414.5	402.5	405.0	406.0	394.0	400.5	393.0	389.5
No. of measurements	2	38	49	49																	
Corrected growth	36.0	369.0	447.0	410.0	407.0	416.0	428.0	443.0	407.0	435.0	420.0	433.0	405.0	420.0	407.5	409.0	410.0	398.0	401.0	396.0	392.0
21. Total growth		141.0	156.5	146.5	128.5	136.5	141.0	141.0	140.0	157.5	158.0	147.0	141.5	137.0	134.5	130.0	130.5	131.5	148.0	147.0	148.0
No. of measurements		14	17	17																	
Corrected growth		149.5	166.0	155.0	136.0	144.5	149.0	149.0	148.0	165.5	166.0	154.0	148.5	143.5	141.0	136.0	136.0	136.5	153.0	152.0	153.5
22. Total growth		100.0	180.5	181.0	189.5	178.0	185.0	187.5	165.0	169.5	176.5	184.0	166.0	182.5	183.0	186.0	171.5	176.0	178.5	186.5	179.5
No. of measurements		14	24																		
Corrected growth		110.0	199.0	199.0	197.5	196.0	203.0	205.5	181.0	185.5	192.5	200.5	181.0	198.5	199.0	202.0	186.0	190.0	192.5	201.0	193.0
23. Total growth		45.5	103.5	95.0	100.0	99.0	96.5	100.0	96.0	92.5	96.5	86.0	78.5	76.5	78.0	78.0	71.0	66.5	65.0	76.5	84.0
No. of measurements		6	11																		
Corrected growth		21.8	117.5	107.6	113.2	111.8	108.7	112.7	108.0	104.0	108.5	96.4	87.7	85.5	87.0	87.0	79.0	74.0	72.0	84.7	94.0
24. Total growth		20.0	18.5	19.0	18.0	17.5	21.5	15.0	18.5	19.0	15.5	14.0	16.5	19.0	18.5	18.5	16.5	20.5	18.5	13.5	11.0
No. of measurements		2																			
Corrected growth		23.4	21.6	22.0	20.9	20.2	24.9	18.0	21.4	22.0	17.8	16.1	18.9	21.8	21.2	21.2	18.8	23.3	21.0	15.2	12.4
25. Total growth		36.5	31.5	30.5	30.5	30.5	31.0	34.5	36.0	38.5	41.5	36.5	30.5	37.0	34.5	33.5	34.5	25.5	24.0	26.5	37.0
No. of measurements		4																			
Corrected growth		43.7	37.6	36.4	36.3	36.2	36.8	40.9	42.6	46.5	49.0	43.0	35.9	43.4	40.4	39.1	40.3	29.7	28.0	30.9	43.0
26. Total growth		37.0	39.5	41.0	43.0	40.5	37.0	39.5	33.5	30.5	31.5	34.5	35.0	35.5	36.5	32.0	30.5	32.5	36.0	37.5	37.5
No. of measurements		4	5	5																	
Corrected growth		45.8	48.8	50.7	53.0	49.8	45.4	48.4	41.0	37.3	38.4	42.0	42.6	43.2	44.3	38.7	36.9	39.2	43.1	45.0	45.0
27. Total growth		14.5	15.0	13.5	15.0	16.0	16.0	14.0	11.0	12.5	12.0	10.5	13.5	14.0	13.0	12.5	12.5	19.0	18.0	15.0	15.5
No. of measurements		2																			
Corrected growth		18.1	18.7	16.8	18.7	20.0	20.0	17.5	13.6	15.5	14.8	13.0	15.3	17.3	16.0	15.3	15.3	23.3	22.0	18.3	18.9
28 & 29. Total growth			4.5	4.0	4.0	3.0	4.0	4.5	4.5	6.0	5.0	5.0	4.0	4.5	4.0	4.5	5.5	6.5	5.0	5.0	4.0
No. of measurements			1	1																	
Corrected growth			5.4	4.8	4.8	3.6	4.8	5.4	5.4	7.2	6.0	6.0	4.8	5.4	4.8	5.4	6.6	7.8	6.0	6.0	4.8
30. Total growth					9.0	7.0	9.5	7.5	9.5	10.5	8.5	10.0	8.5	7.0	9.0	10.0	10.0	10.0	8.0	9.5	9.5
No. of measurements					1	1															
Corrected growth					10.8	8.4	11.4	9.0	11.4	12.6	10.2	12.0	10.2	8.4	10.8	12.0	12.0	12.0	9.6	11.4	11.4
31. Total growth			13.5	16.5	16.0	13.5	13.0	13.5	12.0	10.0	12.5	14.5	12.5	12.0	12.5	10.0	9.0	10.0	13.5	9.5	8.5
No. of measurements			2	2																	
Corrected growth			16.2	19.8	19.2	16.2	15.6	16.2	14.4	12.0	15.0	17.1	15.0	11.4	15.0	12.0	10.8	12.0	16.2	11.4	10.2

Group.	1691–1700 A.D.	1681–90	1671–80	1661–70	1651–60	1641–50	1631–40	1621–30	1611–20	1601–10	1591–1600	1581–90	1571–80	1561–70	1551–60	1541–50	1531–40	1521–30	1511–20	1501–10
1. Total growth	133.0	133.5	82.0	56.5	60.5	51.0														
No. of measurements	7	7	6	5	5	4														
Corrected growth	34.3	33.6	20.0	13.9	140.3	11.5														
2. Total growth	150.5	166.0	171.5	153.0	150.5	145.0	140.0	147.5	149.5	110.5	126.0	121.5	61.0	77.5	73.0	44.5	53.5	41.5	34.0	
No. of measurements	8									8	7	7	5	5	4	3	3	2	2	
Corrected growth	44.8	48.9	50.0	44.2	43.0	41.8	39.0	40.5	40.2	29.2	31.0	30.6	15.4	19.5	18.4	11.0	12.6	9.8	7.7	
3. Total growth	431.5	404.0	435.0	429.5	393.0	384.0	395.0	381.5	382.5	144.5	298.5	318.0	283.5	375.0	354.0	314.5	328.0	314.0	292.0	275.5
No. of measurements	15																			15
Corrected growth	139.1	129.0	137.2	134.1	121.8	117.8	120.0	114.6	113.8	131.0	87.0	91.9	81.2	106.3	98.6	86.1	88.3	82.9	75.3	69.4
4. Total growth	890.0	910.5	940.0	883.0	925.5	963.0	953.0	987.0	1038.0	1048.0	1000.0	1010.5	1065.5	1134.5	1159.0	1137.5	1224.0	1204.0	1250.5	1300.0
No. of measurements	63																			
Corrected growth	333.0	347.0	343.0	318.0	330.0	338.0	332.0	339.0	354.0	353.0	333.0	334.0	347.0	366.0	370.0	359.0	380.0	373.0	384.0	395.0
5. Total growth	337.5	325.0	313.5	332.0	324.5	369.0	343.5	354.5	360.5	367.0	401.0	409.0	429.0	425.5	421.0	391.5	445.5	462.5	441.5	430.0
No. of measurements	21																			
Corrected growth	141.0	134.0	140.0	133.0	128.5	144.5	133.2	136.0	137.0	138.5	150.0	151.0	156.5	153.0	150.0	138.0	155.0	159.0	150.5	145.0
6. Total growth	109.0	121.0	118.0	127.0	135.5	129.0	125.0	139.5	130.0	118.5	133.5	158.5	165.0	178.5	159.5	180.0	165.0	180.0	180.0	174.0
No. of measurements	10																			
Corrected growth	51.1	56.2	53.8	57.3	60.3	57.0	54.4	59.8	55.3	50.6	55.6	65.5	67.3	71.7	63.3	70.6	64.0	69.0	68.4	65.6
7. Total growth	192.5	182.0	201.0	213.0	206.0	208.0	192.5	215.0	227.5	199.0	197.0	194.0	210.5	206.0	193.5	222.5	216.0	224.5	213.5	215.0
No. of measurements	17																			
Corrected growth	104.7	97.6	105.5	111.4	105.9	106.7	96.6	106.4	111.0	95.9	93.6	91.1	97.6	94.1	87.3	100.3	95.4	97.5	91.8	91.5
8. Total growth	314.5	348.5	356.0	333.5	325.5	322.5	312.5	322.0	352.5	328.5	328.0	306.5	345.5	343.5	333.5	331.0	333.0	334.0	368.0	348.5
No. of measurements	26																			
Corrected growth	193.5	212.2	214.8	199.0	192.3	188.5	181.0	184.8	199.3	183.3	180.8	166.7	185.5	182.0	175.0	159.6	167.5	167.5	181.8	170.5
9. Total growth	489.5	471.5	470.5	462.0	466.5	462.5	507.0	496.5	521.5	535.5	506.5	475.5	513.0	505.5	520.5	542.0	545.5	525.5	530.0	544.9
No. of measurements	42																			
Corrected growth	315.0	302.0	300.0	292.5	294.0	288.5	313.0	304.0	316.0	321.3	300.5	280.0	298.0	291.0	296.3	304.0	302.2	287.5	286.5	290.0
10. Total growth	409.0	429.5	444.0	454.0	430.5	412.0	437.5	453.0	454.0	462.5	462.0	473.5	505.0	493.0	500.0	470.5	457.0	440.0	472.0	446.5
No. of measurements	42																			
Corrected growth	277.0	303.5	298.5	304.0	287.0	273.0	289.0	297.0	296.5	301.0	298.0	304.0	323.0	313.0	317.0	296.0	285.0	272.0	288.0	270.5
11. Total growth	771.0	794.5	794.0	813.5	850.0	887.5	845.5	883.0	852.0	810.0	828.0	867.0	821.0	863.0	847.5	865.5	830.5	827.0	816.5	763.0
No. of measurements	75																			
Corrected growth	555.0	569.0	565.0	577.0	599.0	623.0	590.0	615.0	590.0	658.0	568.0	594.0	579.0	586.0	572.0	583.0	557.0	550.0	542.0	503.0
12. Total growth	611.5	639.5	649.0	651.0	664.0	710.5	697.0	653.5	656.0	620.5	621.0	621.0	627.0	610.0	600.0	624.0	599.5	625.5	633.0	631.5
No. of measurements	59																			
Corrected growth	465.0	485.0	496.0	489.0	497.0	530.0	517.0	483.0	483.0	454.0	452.0	450.0	452.0	437.0	427.0	442.0	427.0	446.0	443.0	442.0
13. Total growth	427.5	424.0	430.0	412.0	396.5	404.5	414.5	430.0	442.0	424.5	417.5	425.5	446.5	440.0	430.0	440.5	429.0	418.5	436.5	401.0
No. of measurements	49																			
Corrected growth	340.0	337.0	341.0	326.0	313.0	318.0	325.0	337.0	346.0	230.0	324.0	329.0	344.0	338.0	329.0	335.0	325.0	316.0	328.0	300.0
14. Total growth	480.0	515.5	520.0	517.0	498.0	481.5	452.0	471.0	467.5	463.5	502.5	467.0	505.0	475.5	471.0	463.5	465.5	479.0	477.0	464.5
No. of measurements	51																			
Corrected growth	399.0	428.0	431.0	428.0	413.0	398.0	372.0	385.0	384.0	380.0	410.0	389.0	410.0	386.0	380.0	373.0	373.0	383.0	380.0	369.0
15. Total growth	412.0	399.0	391.0	382.5	365.0	368.0	385.0	382.0	389.5	400.5	391.5	406.0	386.5	414.0	355.0	378.5	354.0	372.5	375.0	353.0
No. of measurements	47																			
Corrected growth	352.0	441.0	333.0	325.0	311.0	313.0	326.5	324.0	330.0	339.0	331.0	342.0	326.0	346.0	298.5	318.0	305.0	311.5	313.0	294.0
16. Total growth	241.0	251.5	243.0	262.5	253.5	255.0	266.0	276.5	285.5	270.5	287.0	268.5	273.5	276.0	269.0	277.5	258.0	257.5	263.5	242.0
No. of measurements	33																			
Corrected growth	213.0	222.0	214.0	231.0	223.0	224.0	234.0	243.0	250.0	237.0	251.0	234.5	238.5	241.0	234.0	241.0	234.0	223.0	228.0	209.0
17. Total growth	343.0	342.5	346.5	346.5	367.5	355.0	357.0	378.5	358.5	350.5	319.5	355.5	365.0	375.0	384.0	364.5	348.5	327.5	324.5	296.5
No. of measurements	47																			
Corrected growth	312.5	312.0	316.0	316.0	334.0	322.0	324.0	342.5	325.5	316.0	288.0	317.5	327.0	336.5	344.0	326.0	312.0	293.0	290.0	264.0
18. Total growth	273.0	250.0	271.5	280.0	267.0	260.0	243.5	247.5	238.5	236.0	229.5	243.0	227.0	224.0	212.0	215.5	225.0	230.0	213.5	194.0
No. of measurements	30																			
Corrected growth	255.0	235.0	254.0	262.0	250.0	243.0	226.5	230.0	222.0	219.5	213.0	225.0	211.5	208.0	196.0	198.5	208.0	201.5	196.0	177.0
19. Total growth	217.5	220.0	213.5	211.5	210.0	202.0	212.5	218.5	193.0	192.0	183.5	192.0	167.0	174.5	167.0	173.0	190.0	186.5	210.0	193.0
No. of measurements	25																			
Corrected growth	211.5	213.5	206.5	204.0	202.5	192.0	204.5	210.0	190.0	184.0	180.5	184.0	159.0	166.5	159.0	164.5	181.0	177.0	200.0	183.0
20. Total growth	417.0	436.5	399.0	398.5	381.0	392.5	385.5	390.5	393.0	401.5	411.0	398.0	420.0	418.0	407.5	407.0	424.5	419.5	378.0	375.5
No. of measurements	49																			
Corrected growth	419.0	438.0	399.5	399.0	380.0	391.0	384.0	388.0	390.0	402.0	408.0	394.0	415.0	413.0	402.0	409.0	417.0	411.0	371.0	368.0
21. Total growth	171.5	159.5	148.5	141.5	145.0	144.5	161.0	147.5	152.0	154.5	138.0	159.5	132.5	147.0	132.5	128.0	137.5	138.5	129.5	120.5
No. of measurements	17																			
Corrected growth	176.5	163.5	152.0	145.0	148.5	147.5	164.5	150.5	155.0	157.5	140.5	162.5	135.9	149.0	134.5	129.5	139.0	139.5	130.5	121.0
22. Total growth	173.0	179.0	183.5	185.5	177.5	194.0	184.5	180.0	186.5	175.0	175.0	169.0	172.0	177.5	184.0	177.0	168.0	166.5	159.5	164.5
No. of measurements	24																			
Corrected growth	186.0	192.5	197.0	199.0	189.5	207.0	197.0	192.0	198.5	186.0	185.5	179.0	182.0	187.5	194.0	186.0	177.0	174.5	167.0	171.5
23. Total growth	80.5	83.0	79.5	83.0	82.0	84.0	86.0	81.0	79.5	75.5	82.5	88.0	81.5	85.0	91.0	92.0	85.5	81.0	75.5	76.5
No. of measurements	11																			
Corrected growth	89.0	91.6	87.7	91.4	90.1	92.3	94.4	88.7	87.0	82.5	89.7	96.7	88.5	92.2	98.8	99.5	92.5	87.5	81.4	82.3
24. Total growth	15.0	15.5	14.0	13.0	13.5	11.5	12.5	13.0	12.5	13.5	13.5	13.5	10.5	11.0	12.0	12.5	14.0	12.5	16.0	12.0
No. of measurements	2																			
Corrected growth	16.9	17.5	15.7	14.6	15.0	12.9	14.0	14.5	14.0	15.1	15.1	15.1	11.7	12.2	13.3	13.8	15.4	13.8	17.6	13.2
25. Total growth	34.0	35.0	32.5	35.0	38.0	31.5	37.0	34.0	36.5	36.5	39.5	37.5	38.5	44.0	40.0	37.0	35.0	32.5	35.5	27.5
No. of measurements	4																			
Corrected growth	39.5	40.5	37.5	40.4	43.8	36.3	42.5	39.0	41.8	41.8	45.2	42.6	43.8	49.8	45.5	42.0	39.7	37.0	40.2	31.2
26. Total growth	38.0	44.5	39.5	40.0	40.5	34.0	40.0	36.5	41.0	38.0	34.0	34.5	37.5	37.0	39.0	45.5	38.5	36.5	36.5	33.5
No. of measurements	5																			
Corrected growth	45.6	53.3	47.2	47.7	48.3	40.4	47.6	43.3	48.6	45.0	40.2	40.7	44.1	43.5	45.8	53.4	45.1	42.7	42.6	39.0
27. Total growth	16.5	11.5	15.5	13.0	14.0	13.0	12.0	12.5	12.0	11.5	12.0	12.0	12.0	12.0	13.5	10.0	12.0	12.5	12.0	10.0
No. of measurements	2																			
Corrected growth	20.1	14.0	18.8	15.7	16.9	15.7	14.5	15.1	14.4	13.8	14.4	14.3	14.3	14.3	15.1	11.9	14.2	14.8	14.2	11.8
28 & 29 Total growth	4.0	4.0	4.5	3.5	6.0	5.5	4.5	5.5	4.0	4.5	4.5	5.0	9.5	2.0	7.0	5.5	6.5	6.5	6.5	6.0
No. of meas'ments	1																			
Corrected growth	4.8	4.8	5.4	4.2	7.2	6.6	5.4	6.6	4.8	5.4	5.4	6.0	11.4	2.4	8.4	6.6	7.8	7.8	7.8	7.2
30. Total growth	6.5	5.5	8.0	10.0	9.5	8.0	10.5	10.0	14.0	14.0	16.0	18.0	12.0	17.0	12.0	8.0	8.0	9.0	7.5	10.0
No. of measurements	1																			
Corrected growth	7.8	6.6	9.6	12.0	11.4	9.6	12.6	12.0	16.8	16.8	19.2	21.6	14.4	20.4	14.4	9.6	9.6	10.8	9.0	12.0
31. Total growth	9.0	10.0	11.5	13.0	13.5	14.0	14.5	13.0	13.5	11.5	13.5	13.0	13.0	13.0	14.5	12.5	16.0	16.5	17.5	16.0
No. of measurements	2																			
Corrected growth	10.8	12.0	13.8	15.6	16.2	16.8	17.4	15.6	16.2	13.8	16.2	15.6	15.6	15.6	17.4	15.0	19.2	19.8	21.0	19.2

Group.	1491–1500 A.D.	1481–90	1471–80	1461–70	1451–60	1441–50	1431–40	1421–30	1411–20	1401–10	1391–1400	1381–90	1371–80	1361–70	1351–60	1341–50	1331–40	1321–30	1311–20	1301–10
3. Total growth.......	201.5	184.5	163.5	54.0	50.5	57.5	76.0	103.5	66.0	....	....	....	....	....	....	....	....	....	....	....
No. of measurements	11	10	8	4	4	4	4	4	2	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	51.9	46.5	41.2	14.1	13.0	14.3	18.2	23.8	14.8	....	....	....	....	....	....	....	....	....	....	....
4. Total growth.......	1267.0	1271.0	1224.5	1377.0	1494.5	1651.5	1655.0	1759.0	1849.5	1932.5	1992.5	2044.5	2248.5	2256.0	2072.0	1956.5	1615.0	659.5	341.0	227.0
No. of measurements	63	....	....	....	....	....	....	....	....	....	63	63	60	60	50	44	34	12	5	3
Corrected growth...	381.0	379.0	361.0	402.0	432.0	472.0	468.0	491.0	506.0	520.0	526.0	527.5	566.0	555.0	510.0	464.0	381.0	155.6	80.5	51.1
5. Total growth.......	437.0	378.0	381.0	412.0	430.0	407.5	454.5	448.5	476.0	472.5	443.0	494.0	515.0	524.5	557.0	608.5	593.0	608.5	465.0	427.0
No. of measurements	21	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	21
Corrected growth...	145.5	125.0	124.5	133.0	137.0	129.0	142.0	139.0	146.0	143.5	133.5	147.0	152.0	153.0	161.0	174.0	167.5	169.6	127.4	114.8
6. Total growth.......	173.5	176.0	172.0	163.0	177.5	182.5	196.5	221.0	220.5	209.5	229.5	258.0	242.5	240.0	254.5	251.0	266.0	264.5	235.0	222.0
No. of measurements	10	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	64.8	64.9	62.6	58.7	63 2	64.3	68.3	76.0	75.0	70.5	76.5	85.0	79.0	77.5	81.2	79.4	83.2	82.0	72.2	67.5
7. Total growth.......	209.5	202.5	216.5	236.0	238.0	269.0	275.0	258.0	285.5	304.5	322.5	370.0	376.0	344.0	340.5	378.0	378.5	380.0	429.0	372.0
No. of measurements	17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	88.4	84.3	89 4	96.4	95.6	106.8	107.8	100.1	109.6	115.7	122.4	138.3	138.8	126.4	122.5	131.6	133.3	132.1	147.8	126.8
8. Total growth.......	320.5	337.0	308.0	322.6	335.6	335.0	366.0	376.5	388.0	377.0	372.5	372.5	422.5	455.5	431.5	478.0	519.5	540.5	526.5	457.5
No. of measurements	26	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	154.0	160 0	144.5	149.2	152.7	151.0	163.2	166.2	168.7	162.2	158 5	157.2	176.0	186.5	176.0	192.0	206.0	212.0	204.2	176.0
9. Total growth.......	547.0	517.5	506.5	485.5	513.5	530.0	552.0	567.5	547.5	593.5	624.5	622.5	648.5	653.5	713.0	738.0	795.0	763.5	829.5	699.0
No. of measorements	42	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	287.5	268.0	258.0	245.0	255.0	260.5	268.0	271.0	258.0	277.0	287.4	283.0	290.5	290.0	311.0	318.5	340.8	324.0	348.0	290.0
10. Total growth.......	455.0	451.5	448.0	457.5	466.5	476.0	467.0	475.5	513.0	473.5	482.0	511.0	485.5	536.5	549.0	548.5	558.5	529.0	515.0	488.5
No. of measurements	42	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	267.0	271.0	264.0	266.5	471.0	274.0	266.0	264.0	280.0	256.0	257.0	268.5	251.5	274 0	277.0	272.0	274.0	257.0	246.0	231.0
11. Total growth.......	742.5	757.5	762.5	791.0	806.5	790.5	834.5	804.5	840.0	818.0	840.0	899.5	899.5	866.5	903.5	959.5	1000.5	979.5	1004.5	942.5
No. of measurements	75	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	487.0	495.0	495.0	511.0	518.0	505.0	527.0	504.0	521.0	502.0	512.0	540.0	536.0	512.0	527.0	553.0	568.0	550.0	556.0	460.0
12. Total growth.......	601.0	576.5	576 5	585.5	671.5	679.5	651.5	646.0	661.0	640.0	663.0	747.5	726.5	692.0	701.5	712.0	721.5	715.0	704.5	672.0
No. of measurements	59	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	418.0	400.0	398.0	402.0	460.0	463.0	440.0	435.0	443 0	426 0	440.0	493.0	479.0	452 0	455.0	458.0	460.0	451.0	440.0	414.0
13. Total growth.......	411.5	415.5	422.5	417.0	422.5	425.0	426.5	418.5	438.0	423.5	455.5	438.5	511.0	482.0	411.5	457.0	502.0	452.0	476.0	443 0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	307.0	308.0	312.0	306.0	309.0	309.0	309.0	302.0	315.0	303.0	324.0	310.0	359.0	337.0	309.0	318.0	348.0	312.0	327.0	303.0
14. Total growth.......	449.0	452.5	455.5	446.0	459.0	466.6	483.0	477.5	464.0	469.5	478.0	466.0	496.0	486.5	490.0	537.0	537.5	502.0	494.0	479.0
No. of measurements	51	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	355.0	356.0	358.0	350.0	359 0	363.0	374.0	368.0	356.0	358.0	363.0	390.0	373.0	364.0	365 0	398.0	396.0	368.0	362.0	349.0
15. Total growth.......	352.5	354.0	358.5	360.0	363.0	387.0	382.5	385.5	377.5	393.5	372.5	391.0	401.0	424.5	407.0	416.5	417.5	409.0	406.0	415.0
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	293.0	294.0	296.0	297.0	298 0	316.0	312.0	314.0	306.0	318.0	300.0	314.0	321.0	338 0	323 0	329.0	329.0	321.0	317.0	322.0
16. Total growth.......	253.5	256.5	266.0	249.5	257.5	249.0	257.0	257.0	241.0	258.0	257.0	266.0	260.5	267.5	286.5	290.5	280.0	293.0	262.5	258.5
No. of measurements	33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	219.0	225.0	228.5	214.0	220.0	212.5	219.0	218.0	204.0	218.0	217.0	223.0	218.0	224.0	239.0	242.0	232 0	242.0	216.5	212.5
17. Total growth.......	298.0	314.5	293.5	288.5	287.0	317.0	324.0	319.0	332.5	353.0	348.5	326.0	339.0	349.0	364.0	388.0	371.0	345.5	346.0	321.0
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	266.0	280.0	260.0	256.0	254.0	280.0	286.0	281.0	292.5	311.0	306.0	286 0	297.0	306 0	318.0	338.0	322.5	300.0	300.0	277.0
18. Total growth.......	204.5	196.0	197.0	202.0	198.5	205.0	209.5	205.5	218.0	210.0	216.0	215.5	224.0	224.0	215.0	225.0	231 0	219 0	217.5	206.0
No. of measurements	30	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	187.0	179.0	180 0	184.0	181.0	187.0	190.0	186.5	198.0	190.0	195.5	195.0	202.0	202.0	194.0	204.0	209.5	198.5	197.0	187.0
19. Total growth.......	199.0	200.5	191.0	209.5	196.0	266.5	227.5	237.5	237.0	227.5	224.0	228.5	246.5	229.0	249.5	227.0	239.5	224.0	228.0	213.5
No. of measurements	25	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	189 0	190.0	180.5	197.5	185.0	251.0	213.5	223.0	222.5	213.0	210.0	214.0	229 0	215.0	232.0	210.5	222.5	208 0	211.5	198.0
20. Total growth.......	367.0	349.0	346.5	359.5	362.0	367.5	382.0	378.0	376.0	394.0	384.0	370.5	374.0	384.0	392.0	396.0	399.5	386.0	373.5	355.0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	358.0	340 0	337 0	350.0	352.0	356.0	370.0	366.0	364.0	380.0	369.0	356.0	359.0	369.0	376.0	379.0	382.0	369.0	357.0	339.0
21. Total growth.......	124.5	119.5	123.0	129.0	133.0	135.5	132.0	130.5	143.0	152.5	138.0	139.0	134.0	130.5	112.5	114.5	126.5	114.5	112.5	117.5
No. of measurements	17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	125.0	120.0	123.0	129.0	133.0	135.5	132 0	130.0	142.5	152.0	137.0	137.5	132.5	128.5	110.5	112.5	124.0	112.0	110.0	115.0
22. Total growth.......	148.5	150.0	148.5	147.0	149.0	156.5	152.0	149.0	148.0	154.5	161.0	167.5	169.5	174.0	184.0	182.5	178.0	173.5	164.5	157.5
No. of measurements	24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	155.5	156.0	154.0	152.0	154.0	161.5	157.0	154.0	153.0	160.0	166.0	172.5	174.5	179.0	189.0	187.0	182.5	177.0	167.5	160.5
23. Total growth.......	71.5	66.5	69.5	72.5	76.5	84.5	89 5	88.0	95.0	97 0	88.0	93.5	94.5	102.5	107.5	118.0	113.0	97.5	86.5	78.5
No. of measurements	11	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	77.0	71.5	74.5	77.5	82.0	90.2	95.5	93 5	101.0	103.0	93.3	99.0	100.0	108.0	103.5	124.5	119.0	102.0	90.5	82.0
24. Total growth.......	14.5	12.5	12.0	10.5	10.5	12.5	11.0	12.5	14 0	13.5	12 5	13 5	12.5	14.0	10.0	10.0	11.5	12.0	11.0	11.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	14.8	13.7	13.1	11.5	11.5	13.6	12 0	13.6	15.3	14.7	13.6	14.6	13.5	15.1	10.8	10.8	12.4	12.9	11.9	12.4
25. Total growth.......	30.5	31.5	29.5	25.0	29.5	25.0	25.5	25.0	35.0	30.0	29.0	27.0	30.5	29.0	31.5	37.0	34.5	37.0	34.5	38.0
No. of measurements	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	34.4	35.5	33.2	28.1	33.1	28.0	28.5	28.0	39.0	33.5	32.2	30 0	33.8	32 0	34.9	39.9	38.1	39.8	38.0	41.7
26. Total growth.......	36.0	32.5	37.0	35.5	36.0	40.0	39.0	46.0	39.0	34.0	34.5	37.5	33.5	32 0	32.5	34.0	33.0	35.0	37.5	35.5
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	41.9	37.8	42.9	41.1	41.6	46.2	45.0	53.1	44.8	39.1	39 6	43.0	38.4	36 6	37.2	38.8	37.6	39.8	42.7	40.3
27. Total growth.......	13.5	14.0	14 5	15.0	14.5	13.5	12.5	14 0	14.5	12.0	13.5	14.0	14.0	16.0	12.0	14.0	13.5	15.5	14.5	16.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	15.9	16.5	17.1	17.6	17.0	15.8	14.6	16.3	16 9	14.0	15.7	16 2	16.2	18.5	13.9	16.2	15.6	17.9	16.7	18.4
28 Total growth.....	4.0	5.0	5.0	4.5	4.5	6.0	7.0	7.0	7.0	7.0	6.5	7.5	7.5	8.5	9.0	12.0	12.0	15.0	12.0	11.5
& No. of meas'ments	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
29. Corrected growth.	4.8	6.0	6.0	5.4	5.4	7.2	8.4	8.4	8.4	8.4	7.8	9.0	9.0	10.2	10.8	14.4	14.4	18.0	14.3	13.7
30. Total growth.......	10.0	6.5	7.5	8.0	6.5	7.0	7.0	7.0	8.0	5.5	7.5	9.0	7.5	10.0	13.0	13.5	10.0	10.0	14.0	12.0
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	12.0	7.8	9.0	9.6	7.8	8.4	8.4	8.4	9.6	6.6	9.0	10.8	9.0	12.0	15.6	16.2	12.0	12.0	16.7	14.3
31. Total growth.......	11.0	11.5	13.5	14.5	14.5	12.0	14.0	14.0	13.0	14 0	10.5	15.0	16.0	14 5	21.0	18.5	17.5	15.5	13.5	11.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	13 2	13.8	16.2	17.4	17.4	14.4	16.8	16.8	15.6	16.8	12.6	18.0	19.2	17.4	26.2	22 2	21.0	18.6	16.2	13.2

TABLE F.—*Growth of Sequoia washingtoniana by Groups for each Decade*—Continued.

Group	1290–1300 A.D.	1281–90	1271–80	1261–70	1251–60	1241–50	1231–40	1221–30	1211–20	1201–10	1191–1200	1181–90	1171–80	1161–70	1151–60	1141–50	1131–40	1121–30	1110–20	1101–10
5. Total growth......	415.5	357.5	319.5	330.0	307.0	258.5	249.5	265.0	167.5	36.5	31.5	....	....	....	....	....	....	....	....	....
No. of measurements	19	19	16	14	14	11	11	9	6	2	2	....	....	....	....	....	....	....	....	....
Corrected growth...	117.6	92.3	82.5	87.5	77.4	65.2	61.4	62.5	39.5	8.6	7.1	....	....	....	....	....	....	....	....	....
6. Total growth.......	235.5	226.5	222.5	233.0	225.5	210.5	198.0	240.0	236.0	237.0	267.0	214.5	209.0	196.5	231.5	250.5	233.0	97.5	....	....
No. of measurements	10	....	....	....	....	....	....	10	9	9	9	9	8	8	8	8	6	3	....	....
Corrected growth...	70.8	67.5	66.5	68.0	65.2	60.2	56.0	67.0	65.8	65.0	71.8	56.6	54.0	49.5	57.0	59.0	53.7	22.0	....	....
7. Total growth......	401.0	367.0	338.5	309.5	308.0	309.5	304.0	310.5	387.5	360.5	366.5	319.5	377.5	445.5	384.0	357.5	369.0	394.0	400.5	408.5
No. of measurements	17	....	....	....	....	....	....	....	....	....	....	....	....	17	15	15	15	15	15	15
Corrected growth...	135.0	122.0	111.8	100.8	99.5	98.8	97.0	107.7	121.3	110.7	111.3	105.0	112.5	131.3	112.0	103.2	105.5	111.5	111.6	111.8
8. Total growth......	441.0	430.0	421.0	457.0	437.0	440.0	465.0	473.0	496.5	490.8	454.5	469.5	474.5	471.5	456.5	507.5	532.5	558.0	604.0	616.0
No. of measurements	26	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	167.5	162.0	157.5	169.0	159.3	158.2	165.1	166.5	172.5	168.5	153.0	156.1	156.7	153.6	141.3	162.0	168.3	175.0	189.0	191.0
9. Total growth.......	632.0	664.5	680.0	619.0	655.5	700.5	712.5	810.0	746.0	767.5	709.0	734.0	756.5	716.0	697.0	751.0	783.5	845.0	913.5	879.5
No. of measurements	42	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	258.8	268.0	271.0	244.0	255.2	270.4	272.2	307.1	280.5	284.6	260.0	267.7	270.5	253.5	244.0	260.0	268.7	286.2	305.6	291.7
10. Total growth......	495.0	479.0	519.0	543.5	547.5	588.5	562.5	585.5	620.0	596.0	567.0	565.5	573.5	588.5	614.0	645.5	697.5	706.5	730.5	692.0
No. of measurements	42	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	231.0	220.0	236.0	246.5	243.0	257.0	243.0	251.0	263.0	250.0	237.0	232.0	231.5	235.0	242.0	250.5	269.0	270.0	277.0	260.0
11. Total growth.......	873.0	879.5	858.0	874.5	880.5	904.0	967.0	968.5	992.0	927.0	945.0	957.5	990.5	959.0	988.0	1000.0	1085.5	1112.5	1115.2	1147.5
No. of measurements	75	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	472.0	468.0	451.0	453.0	450.0	455.0	480.0	475.0	480.0	443.0	445.0	445.0	455.0	435.0	445.0	442.0	473.0	482.0	478.0	486.0
12. Total growth......	663.0	686.0	691.5	737.0	755.5	730.0	741.0	748.5	707.5	783.5	797.0	796.5	798.0	783.0	769.0	782.0	818.5	810.5	824.5	848.0
No. of measurements	59	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	405.0	417.0	416.0	437.0	443.0	421.0	424.0	422.0	393.0	455.0	431.0	425.0	420.0	407.0	393.0	395.0	409.0	398.0	400.0	406.0
13. Total growth......	445.5	461.0	463.5	478.0	463.5	452.5	442.0	458.0	446.5	458.0	459.5	433.0	502.0	486.5	459.5	481.0	524.0	522.0	522.0	520.0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	303.0	311.0	312.0	320.0	308.0	301.0	292.0	300.0	290.0	293.0	291.0	272.0	312.0	298.0	280.0	290.0	311.0	306.0	302.0	297.0
14. Total growth.......	510.5	509.0	516.0	520.0	507.5	516.0	493.5	522.0	502.5	532.0	567.5	515.0	529.5	506.5	509.5	506.0	532.0	553.0	565.5	548.0
No. of measurements	51	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	370.0	367.0	371.0	372.0	362.0	367.0	319.0	365.0	350.0	368.0	391.0	353.0	360.0	343.0	313.0	338.0	352.0	362.0	367.0	352.0
15. Total growth......	392.5	387.5	371.0	381.0	399.0	389.0	386.0	418.5	381.5	407.0	405.0	374.0	368.5	385.5	392.5	395.5	393.0	399.0	412.5	414.5
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	302.5	298.0	283.5	292.0	302.6	293.0	290.0	312.0	284.0	302.0	299.0	274.5	270.0	281.0	285.0	286.0	283.0	286.0	294.5	294.0
16. Total growth......	214.5	215.0	232.5	249.5	255.5	257.5	258.5	261.0	261.5	262.0	270.0	265.0	263.0	255.5	256.0	265.0	275.0	289.0	278.5	272.0
No. of measurements	33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	200.0	200.0	189.0	202.0	206.0	206.5	206.5	207.0	206.5	208.0	211.0	206.0	203.5	197.0	196.0	202.5	209.0	218.5	210.0	205.0
17. Total growth......	319.0	330.0	334.5	323.0	332.0	328.5	339.5	361.0	343.0	345.0	351.0	347.0	361.0	343.5	339.5	338.5	348.0	345.0	322.0	348.5
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	273.0	283.0	286.0	275.0	282.0	279.0	288.0	305.0	289.0	289.0	294.0	[illegible]	303.0	284.0	280.0	278.0	281.0	280.0	260.0	281.0
18. Total growth......	205.0	208.5	225.0	227.5	229.0	230.0	230.5	221.5	221.0	222.5	250.0	208.5	213.0	209.5	209.5	218.0	221.5	229.5	224.0	222.0
No. of measurements	30	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	185.5	188.0	203.0	205.0	204.0	204.0	204.0	197.0	196.5	198.0	219.0	181.0	185.0	181.5	181.0	188.0	191.0	197.0	191.0	189.0
19. Total growth......	211.5	199.0	205.0	211.0	204.5	199.0	201.5	198.0	201.0	195.5	205.0	205.0	204.0	203.5	212.0	217.5	187.5	197.0	195.0	198.0
No. of measurements	25	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	196.0	184.0	190.0	195.0	189.0	183.5	185.0	181.5	184.5	179.0	187.5	187.5	186.5	186.0	193.0	198.0	171.0	179.0	177.0	179.0
20. Total growth......	361.5	361.5	375.0	361.5	381.0	382.5	378.0	389.0	371.0	371.0	311.0	355.5	343.0	350.5	361.5	367.5	368.0	395.5	382.0	370.0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	344.0	344.0	356.0	343.0	361.0	362.0	358.0	368.0	353.0	350.0	321.0	334.0	322.0	328.0	339.0	343.0	343.0	368.0	355.0	344.0
21. Total growth......	126.5	125.5	116.0	115.0	112.5	117.0	121.0	124.0	133.5	137.5	138.0	135.0	133.0	135.5	119.0	124.5	122.5	126.0	124.0	119.0
No. of measurements	17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	123.5	122.5	113.0	112.0	109.5	113.5	117.0	120.0	129.0	133.0	133.5	130.0	128.0	130.5	114.5	119.5	122.5	120.5	118.5	114.0
22. Total growth......	161.0	159.5	166.5	172.0	168.5	172.0	160.5	171.0	179.0	173.0	175.0	162.0	[illegible]	148.0	157.0	156.0	162.0	177.5	188.5	186.5
No. of measurements	24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	164.0	162.0	169.0	174.0	170.5	173.5	162.0	172.5	180.0	174.0	175.5	162.5	161.0	148.0	157.0	156.0	162.0	177.5	188.0	186.0
23. Total growth......	67.0	73.0	73.0	75.0	87.0	93.0	95.5	92.5	83.0	75.5	79.5	79.0	85.0	78.5	77.5	80.0	97.0	70.5	71.5	74.5
No. of measurements	11	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	70.0	76.3	76.2	78.0	90.2	96.5	99.0	96.0	86.0	78.0	82.0	81.5	88.0	81.0	80.0	82.0	99.5	72.0	73.0	77.0
24. Total growth......	10.0	13.5	14.5	12.5	11.5	12.0	14.0	13.5	13.5	13.5	11.0	11.5	14.0	10.0	11.5	10.5	15.5	16.0	14.5	15.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	10.8	14.4	15.5	13.3	12.3	12.8	14.9	14.3	14.3	14.3	11.6	12.1	14.7	10.5	12.1	11.0	16.2	16.7	15.2	15.7
25. Total growth......	34.0	28.0	26.0	33.5	37.5	33.0	34.5	36.0	33.5	29.5	29.0	27.0	23.5	29.0	29.0	32.0	30.0	27.0	21.5	24.5
No. of measurements	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	37.3	30.6	28.4	36.7	41.0	36.1	37.6	39.3	36.4	32.2	31.6	31.5	25.4	31.2	31.2	34.4	32.1	28.9	23.1	26.2
26. Total growth......	37.0	30.0	39.5	47.5	36.0	34.5	31.5	32.0	28.0	36.5	33.0	35.5	33.0	34.0	36.0	30.0	30.5	29.5	34.5	31.5
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	41.9	44.0	44.6	53.5	40.6	38.8	35.4	36.0	31.4	40.8	36.9	39.7	36.8	37.9	40.1	33.3	33.8	32.7	38.2	34.8
27. Total growth......	13.0	13.5	16.0	13.5	11.5	15.0	12.0	15.0	14.5	14.0	12.5	16.0	13.5	17.0	14.5	16.0	15.0	14.5	14.5	14.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	14.9	15.5	18.3	15.4	13.1	17.1	13.6	17.0	16.5	15.9	14.1	18.1	15.2	19.2	16.3	18.0	16.9	16.2	16.2	16.2
28 & 29 Total growth......	7.5	6.5	6.0	4.5	6.0	5.5	5.0	5.5	6.0	4.0	4.5	4.5	4.5	1.0	5.0	5.0	5.0	6.0	6.0	5.5
No. of meas'ments	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	8.9	7.7	7.1	5.3	7.1	6.5	5.9	6.5	7.0	4.7	5.3	5.3	5.3	4.7	5.8	5.8	5.8	7.0	6.9	6.4
30. Total growth......	9.0	9.0	10.0	14.0	13.0	17.0	13.0	12.0	14.5	12.5	18.0	16.0	14.0	12.5	10.5	13.0	9.0	9.0	12.0	11.0
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	10.6	10.6	11.8	16.5	15.3	20.0	15.3	14.1	17.0	1.46	21.0	18.7	16.3	11.5	12.2	15.1	10.4	10.4	13.9	12.7
31. Total growth......	18.5	15.5	16.0	11.5	11.0	10.5	8.0	8.0	9.0	8.0	7.5	10.5	7.5	7.0	7.0	5.5	6.0	7.5	8.0	8.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	22.2	18.6	19.2	13.8	13.2	12.6	9.6	9.6	10.8	9.6	9.0	12.5	8.9	8.3	8.3	6.5	7.1	8.9	9.4	10.0

Group.	1091–1100 A.D.	1081–90	1071–80	1061–70	1051–60	1041–50	1031–40	1021–30	1011–20	1001–10	991–1000	981–90	971–80	961–70	951–60	941–50	931–40	921–30	911–20	901–10
7. Total growth	398 0	461.5	428.0	398.5	287.0	297.5	240.5	189 5	157.0	91.0	....	....	....	....	....	....	....	....	....	....
No. of measurements	15	15	15	14	11	11	9	7	5	3	....	....	....	....	....	....	....	....	....	....
Corrected growth...	107.0	121.8	110.6	100.5	72.2	73.2	59.2	44.7	37.1	20.6	....	....	....	....	....	....	....	....	....	....
8. Total growth.......	604.5	606.5	615.5	567.5	572.0	577.5	567.5	614.0	649.0	659.5	624.5	607.5	549.5	485.0	491.0	493.5	462 5	346.0	173.0	97.5
No. of measurements	26	....	....	....	....	....	....	....	....	....	26	26	26	22	22	21	17	14	8	4
Corrected growth...	185.7	184.8	185.5	169.1	168.5	168.5	164.0	175.8	183.8	184.0	171.0	163.4	145.0	125.1	124.0	121.5	113.8	81.6	40.8	22.5
9. Total growth.......	960.0	992.0	882.0	907.5	1011.0	909.5	920.0	1022.5	1039.5	1126.5	1142.5	929.5	921.0	791.5	797.5	764.0	726.5	762.5	723.0	628.0
No. of measurements	42	....	....	....	....	....	....	....	....	....	....	....	....	....	42	40	40	40	40	40
Corrected growth...	314.5	322 0	283.0	288.6	318.0	284 0	284.5	313.0	313.8	336.0	338.0	272.2	267.0	227.0	226.4	216.8	203.5	209.5	195.2	167.0
10. Total growth.......	790.0	746.0	775.0	763.5	789.5	908.5	929.5	972.0	1023.0	1063.5	965.5	1056.5	991.0	1011.0	1021.5	965.5	1038.5	1086.5	1180.5	1182.5
No. of measurements	42	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	293.0	374.0	381.0	273.0	279.0	318.0	321.5	333.5	347 0	356.0	320.5	346.0	321.0	324.5	325.0	304.0	324.0	336.0	361.0	357.0
11. Total growth.......	1114.1	1167.5	1176.5	1200.5	1244 0	1330.0	1394.0	1523.5	1534.5	1727.0	1555.0	1436.5	1393.0	1439.0	1515.0	1528.5	1600.5	1678.5	1613.0	1734.0
No. of measurements	75	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	468.0	484.0	482.0	486.0	497.0	524.0	545.0	590.0	590.0	658.0	584 0	534.0	512.0	522.0	545.0	541.0	560.0	582.0	553.0	588.0
12. Total growth.....	833.0	871.5	836.5	845.0	845.0	868.5	893.0	974.5	1011.0	1004.5	969.0	909.0	931.0	958.5	994.0	1008.5	988.5	1011.0	1116.5	1181.0
No. of measurements	59	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	59
Corrected growth...	393.0	408.0	385.0	386.0	380.0	386.0	392.0	425.0	436.0	444.0	408.0	378.0	382.0	383.0	398 0	402.0	389.0	395.0	433.0	452.0
13. Total growth.......	536.0	537.0	565.0	535.5	568.0	592.0	622.0	650.0	661.5	686.5	662.5	608.5	618.0	609.0	629.0	625.0	667.0	702.5	723.0	729.0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	302.0	298.0	310.0	290.0	303.0	312.0	323.0	334.0	336.0	343.0	326.0	296.0	296.0	288.0	295.0	289.0	304.0	317.0	323.0	321.0
14. Total growth.......	553.0	581.5	575.0	531.0	532.5	594.0	592.0	617.5	685.0	646.0	622.0	614.5	621.0	610.5	619.0	621.5	619.0	634.5	685.5	682.0
No. of measurements	51	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	352.0	366.0	358.0	327.0	325.0	356.0	350.0	362.0	394.0	368.0	349.0	339.0	339.0	329.0	329.0	327.0	322.0	324 0	345.0	341.0
15. Total growth.......	404.0	395.0	417.5	408.0	440.0	427.5	429.5	445.5	468 5	472.0	456.5	458.0	445.0	418.0	407.5	431.5	454.5	480.5	502.0	501.5
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	285.0	277.0	292.0	284.0	304.0	293 0	292.0	300.0	312.0	312.0	299.0	297.0	285.0	265.5	256.0	268.0	278.0	290.0	290.5	295.0
16. Total growth.......	293.0	289.5	312.0	304.0	288.0	294.0	320.0	318.5	320.5	321.0	319.5	300.5	326.5	307.0	306.0	317.5	329.0	334.5	327.0	343.5
No. of measurements	33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	219.0	216.0	231.5	225.0	212.0	215.0	233.5	231.0	231.0	230.0	228.0	213.0	230.0	215.0	213.0	219.0	224.5	226 0	218.5	227.0
17. Total growth.......	332.0	353.5	348.0	331.5	353.0	375.5	378.5	403.0	419.5	392.5	420.5	377.0	386.0	391.5	391.5	380.5	367.5	390.0	390.5	381.5
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	266.0	281.0	276.0	262.0	277.0	293.0	294.0	312.0	322.0	302.0	322.0	288.0	293.0	296.0	295.0	286.0	275.0	291.0	289.0	282.0
18. Total growth.......	238.0	208.0	206.0	211.0	214.0	250.0	254.0	257.5	214.0	259.5	262.5	226.0	234.0	243.0	250.5	245.5	270.0	262 5	272.0	249.0
No. of measurements	30	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	202.0	174.5	173.0	177.0	179.0	207 0	210.0	213.0	200.0	215.5	213.5	181.0	188.0	193.0	199.5	195.0	214.0	207.0	214.0	195.0
19. Total growth.......	204.5	208.0	216.0	207.0	212.0	197.5	209.5	201.5	204.0	217.0	209.0	219.0	224.5	210.0	209.5	195.5	202.0	204.5	206.0	215.5
No. of measurements	25	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	185.0	187.0	194.0	185.0	189.0	176.0	185.5	178.0	180.0	191.0	183.0	191.0	195.0	182.0	181.0	168.0	173.0	174 0	175.0	182.5
20. Total growth.......	365.0	358.0	362.0	393.5	397.0	411.0	420.0	435.0	419.5	411.0	386.5	410.5	398.0	392.0	383.5	390.0	384.0	395.0	396.0	405.0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	339.0	333.0	336.0	365.0	367.0	380.0	387.0	417.0	384.0	376.0	353.0	373.0	361.0	354.0	346.0	350.0	344 0	352.0	352.0	358.0
21. Total growth.......	125.5	130.0	129.0	121.5	125.0	131.5	141.0	138.0	130.5	125.0	118.0	125.5	113.5	122.5	117.5	119.0	116.5	125.0	125.5	132.0
No. of measurements	17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	120.0	124.0	123.0	115.5	119.0	125.0	134.0	131.0	124.0	118.0	112.0	118.5	107.0	115.0	110.5	111.0	109.0	116.5	117.0	122 5
22. Total growth.......	197.5	182.5	185.5	176.5	179.0	177.0	188.5	199.0	187.5	184.0	177.5	178.5	159.5	162.5	158.0	155.5	171.0	170.0	179.0	165.0
No. of measurements	24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	196.5	181.0	184.0	174.5	177.0	174.5	185.5	195.5	184.0	180.5	174.0	175.0	155.5	158.5	154 0	151.0	166.5	165.5	174.0	160.0
23. Total growth.......	73.0	72.0	81.0	82.0	78.5	81.5	80.5	89.0	97.5	97.5	71.0	70.0	65.5	72.5	68.5	62.5	66.5	66.5	67.5	67.5
No. of measurements	11	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	74.0	73.0	82.0	83.0	79.5	82.5	81.5	90.0	98.0	98.0	71.0	70.0	65.5	72.5	68.5	62.5	66.5	66.5	67.5	67.5
24. Total growth.......	15.0	13.0	13 0	15.0	13.0	15.5	18.5	16.5	15.0	14.5	11.5	11.5	13.0	12.5	11.5	12.0	13.5	12.5	12.5	11.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	15.7	13.6	13.6	15.6	13.5	16.1	19.1	17.0	15.5	15.0	12.0	11.9	13.4	12.9	11.9	12.4	13.9	12.8	12.8	11.8
25. Total growth.......	23.5	26.0	23.5	24.0	27.5	28.0	28.0	32.0	27.0	25.0	28.5	29.5	24.5	23.5	29.0	24.5	22.5	29.5	29.0	30.0
No. of measurements	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	25.2	27.7	25.1	25.6	29.1	29.6	29.6	33.8	28.6	26.4	29.2	31.2	26.8	25.0	30.5	25.2	23.6	30.9	30.3	31.3
26. Total growth.......	28.0	31.0	33.5	31.5	34.5	40.0	37.5	32.5	28.5	26.5	32.5	29.5	31.0	30.0	30.0	30.0	29.5	31.5	29.0	26.0
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	30.9	34.1	36.8	34.6	37.9	43.8	41.0	35.6	31.1	28.9	35.4	32.1	33.7	32.5	32.5	32.5	31.9	34.0	31.2	28 0
27. Total growth.......	13.5	13.0	17.0	17.5	19.5	17.5	19.0	17.5	19.5	18.5	14.0	12.0	11.5	13.0	12.5	11.5	14.0	15.5	18.5	17.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	15.1	14.5	19.0	19.5	21 6	19.4	21.1	19.4	21.6	20.4	15.4	13.2	12.6	14.3	13.7	12.6	15.3	16.1	20.2	18.5
28 Total growth.. ..	5.5	6.0	7.0	8.0	8.0	10.0	7.0	10 0	10.0	10.0	9.5	10.0	9.5	9.5	6.5	4.5	3.5	3.5	3 5	3.0
& No. of meas'ments	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
29. Corrected growth.	6.4	6.9	8.1	9.2	9.2	11.5	8.0	11.4	11.4	11.4	10.8	11.4	10.8	10.8	7.4	5.1	4 0	4.0	3.9	3.4
30. Total growth.......	10.0	10.0	14.0	14.0	14.0	21.0	21.0	16.0	18.0	16.0	13.0	11.0	12.0	12.5	11.5	11.0	13.0	11.0	11.0	10.0
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	11.5	11.5	16.1	16.0	16.0	24.0	24.0	18.3	20.5	18.3	14 8	12.5	13.6	14.2	13 0	12.4	14.7	12.4	12.4	11.2
31. Total growth.......	8.5	9.5	10.0	12.5	13.5	12.0	12.5	13.5	14.0	12 5	8.0	8.0	9.5	8.5	11.0	8.5	9.0	12.0	11.0	11 0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	10.0	11 1	11 7	14.6	15.7	14.0	14.5	15.7	16.2	14.5	9 2	9 2	11.0	9.8	12.7	9.8	10.3	13.7	12.6	12.6

Group.	891–900 A.D.	881–90	871–80	861–70	851–60	841–50	831–40	821–30	811–20	801–10	791–800	781–90	771–80	761–70	751–60	741–50	731–40	721–30	711–20	701–10
8. Total growth	32.0	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	7.2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
9. Total growth	746.5	601.0	515.0	469.0	385.0	456.0	298.5	318.0	289.5	42.0	....	....	....	....	....	....	....	....	....	....
No. of measurements	34	31	29	23	19	19	14	13	10	2	....	....	....	....	....	....	....	....	....	....
Corrected growth	198.5	156.2	131.0	120.5	97.6	112.9	74.2	75.4	65.5	9.5	....	....	....	....	....	....	....	....	....	....
10. Total growth	1104.5	1037.5	992.0	962.0	1017.5	990.0	1032.0	892.5	1049.5	976.5	1079.5	1096.5	805.5	499.5	454.0	439.5	417.0	277.5	289.5	103.5
No. of measurements	42	....	....	....	....	....	....	....	....	....	42	42	24	24	22	18	18	13	11	5
Corrected growth	330.0	307.0	291.0	279.0	292.0	281.0	289.0	246.0	283.0	259.6	280.3	279.0	214.5	129.7	115.3	110.5	101.5	65.8	66.8	23.4
11. Total growth	1763.5	1774.5	1697.5	1736.0	1727.5	1727.5	1688.0	1694.5	1618.5	1666.5	1658.5	1637.5	1583.5	1486.5	1494.5	1452.0	1539.5	1526.5	1450.5	1464.5
No. of measurements	75	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	75	73	73	73
Corrected growth	593.0	589.0	458.0	564.0	456.0	549.0	532.0	529.0	500.0	510.0	503.0	491.0	467.0	437.0	435.0	418.0	437.5	433.0	405.0	402.0
12. Total growth	1121.5	1055.5	1055.5	1119.5	1147.5	1172.5	1201.0	1180.5	1212.0	1203.0	1239.0	1253.0	1288.5	1218.5	1332.5	1417.5	1373.5	1455.0	1464.5	1644.0
No. of measurements	59	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	59
Corrected growth	423.0	392.0	388.0	404.0	413.0	418.0	425.0	412.0	418.0	412.0	418.0	420.0	425.0	398.0	432.0	455.0	437.0	458.0	457.0	508.0
13. Total growth	726.0	763.0	755.0	731.0	740.0	754.0	762.5	766.0	839.5	821.0	859.5	828.0	793.5	778.5	826.5	809.0	822.0	831.5	893.5	953.0
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	316.0	330.0	324.0	308.0	308.0	309.0	309.0	309.0	334.0	325.0	337.0	321.0	304.0	294.0	308.0	298.0	300.0	300.0	320.0	336.0
14. Total growth	709.0	647.5	651.0	679.0	678.5	665.5	693.5	727.0	717.5	724.0	752.0	778.5	746.0	713.5	798.0	815.5	812.0	773.5	809.5	822.0
No. of measurements	51	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	348.0	314.0	314.0	322.0	318.0	308.5	318.0	330.0	322.0	321.0	330.0	336.0	318.0	300.0	332.0	336.0	332.0	313.0	325.0	337.0
15. Total growth	499.0	498.0	503.0	510.5	506.0	496.5	497.0	506.0	474.0	494.0	510.0	513.5	525.5	518.0	579.5	549.0	531.0	527.0	540.0	581.0
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	290.0	285.5	284.0	284.0	278.5	268.0	264.5	268.0	246.5	254.0	259.0	257.0	260.0	254.0	280.0	261.5	250.0	245.0	249.0	265.0
16. Total growth	330.5	324.5	309.0	301.0	299.0	325.5	343.0	328.5	329.5	328.0	335.5	333.5	321.0	336.0	355.0	354.0	371.0	369.0	365.5	379.0
No. of measurements	33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	217.0	210.5	198.0	191.0	187.0	201.0	209.0	197.5	196.0	192.0	193.5	190.0	180.5	186.0	195.0	194.0	197.0	194.0	190.0	194.0
17. Total growth	393.5	384.5	352.5	360.0	370.5	391.0	390.5	395.5	405.5	405.0	407.0	400.0	397.5	400.5	411.5	414.0	434.0	393.0	401.0	408.5
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	289.0	281.0	256.0	260.0	266.0	280.0	277.0	277.0	282.0	278.0	276.0	269.0	264.0	264.0	269.0	268.0	276.0	247.0	245.0	246.0
18. Total growth	257.0	245.5	241.5	248.0	247.5	228.5	248.5	246.1	246.5	254.5	258.0	261.0	254.0	263.5	270.5	258.5	252.0	263.5	267.0	255.0
No. of measurements	30	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	200.0	190.0	186.0	190.0	188.0	173.0	187.0	185.0	184.0	189.0	191.0	192.0	186.0	192.0	195.0	184.0	178.0	184.5	185.0	175.0
19. Total growth	196.5	202.5	191.0	197.5	197.5	188.0	192.5	190.5	193.0	210.5	212.5	196.5	205.5	207.0	207.0	192.5	194.5	191.5	182.5	184.0
No. of measuremeots	25	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	165.0	169.5	159.0	164.0	163.0	154.5	157.5	155.0	157.0	170.0	171.0	157.5	164.0	164.5	163.5	151.0	152.0	149.0	141.0	142.0
20. Total growth	381.0	376.0	399.5	374.0	392.5	367.5	382.0	373.5	378.5	376.0	392.5	394.0	398.5	404.5	417.0	429.5	399.5	401.5	386.5	381.5
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	336.0	331.0	350.0	327.0	342.0	318.0	330.0	321.0	323.0	320.0	332.0	332.0	334.0	338.0	346.0	354.0	329.0	330.0	316.0	310.0
21. Total growth	132.5	124.0	121.0	111.5	109.5	117.0	112.5	111.0	127.0	124.5	122.5	114.0	111.0	115.0	119.0	115.5	114.5	105.5	108.0	112.0
No. of measuremeots	17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	122.5	114.0	111.0	102.0	100.0	106.0	102.0	100.0	104.5	112.0	109.5	102.0	98.5	101.0	104.0	101.0	99.5	91.0	92.5	96.0
22. Total growth	166.0	159.0	164.0	155.5	159.0	170.0	166.0	169.0	176.5	166.5	169.0	156.5	149.5	161.0	160.0	151.5	154.5	156.5	154.0	162.0
No. of measurements	24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	161.0	154.0	158.5	150.0	153.0	163.5	159.5	162.0	169.0	159.0	161.0	148.0	141.0	151.5	150.0	142.0	144.0	145.5	143.0	150.5
23. Total growth	69.0	71.5	68.5	76.5	78.0	70.5	71.5	64.5	73.0	74.5	78.0	71.0	73.0	69.0	77.0	76.5	64.0	68.5	71.0	72.5
No. of measurements	11	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	69.0	71.5	68.0	76.0	77.2	69.9	70.8	63.8	72.1	73.5	76.9	70.0	71.8	67.8	75.5	73.8	62.5	66.7	69.0	70.2
24. Total growth	11.5	13.5	10.0	12.0	11.5	11.0	9.5	8.5	8.5	10.0	11.5	11.0	12.5	10.5	11.5	13.5	11.0	11.5	13.5	10.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	11.8	13.8	10.2	12.2	11.7	11.2	9.6	8.6	8.6	10.1	11.6	11.1	12.5	10.5	11.5	13.5	10.9	11.4	13.4	9.9
25. Total growth	23.5	25.5	20.0	21.5	21.5	20.5	22.0	23.5	23.5	25.0	24.5	26.0	25.0	25.5	25.5	27.5	24.0	24.0	23.0	24.0
No. of measurements	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	24.5	26.5	20.8	22.3	22.3	21.3	22.8	24.3	24.3	25.8	25.2	26.7	25.7	26.2	26.1	28.1	24.5	24.5	23.5	24.5
26. Total growth	25.5	29.0	28.0	25.0	26.5	33.5	26.5	27.0	24.0	23.5	25.0	29.5	23.5	22.5	25.5	24.0	26.0	29.0	26.0	29.5
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	27.5	31.1	30.0	26.8	28.3	36.7	28.3	28.8	25.6	25.0	26.5	31.3	24.9	23.8	26.9	25.3	27.4	30.5	27.3	31.0
27. Total growth	18.0	11.0	13.5	12.5	11.5	13.0	14.5	11.0	11.5	16.0	13.5	11.5	11.0	14.0	13.5	14.0	11.5	12.5	9.5	12.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	19.6	11.9	14.6	13.5	12.4	14.0	15.6	11.8	12.4	17.2	14.5	12.3	11.8	15.0	14.4	14.9	12.2	13.3	10.0	13.3
28 Total growth	4.0	4.0	3.0	3.0	4.0	3.5	4.0	4.5	4.5	4.5	4.5	5.0	5.0	6.0	7.0	7.5	7.5	8.0	7.0	5.5
& No. of meas'ments	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
29. Corrected growth	4.5	4.5	3.4	3.4	4.5	3.9	4.5	5.0	5.0	5.0	5.0	5.5	5.5	6.6	7.7	8.3	8.3	8.8	7.7	6.0
30. Total growth	8.0	10.0	10.5	16.5	10.0	11.0	10.5	11.5	7.5	7.5	8.0	10.0	9.5	9.5	11.0	9.0	9.0	10.5	9.5	10.0
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	9.0	11.2	11.8	18.5	11.1	12.3	11.7	12.8	8.3	8.3	8.8	11.1	10.6	10.6	12.1	9.9	9.9	11.5	10.5	11.0
31. Total growth	9.0	7.0	6.5	8.5	9.5	8.0	9.5	11.0	9.5	10.0	10.5	10.0	10.0	12.0	9.5	10.0	10.0	7.0	10.0	10.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	10.3	8.0	7.4	9.7	10.8	9.1	10.7	12.4	10.7	11.3	11.8	11.2	11.2	13.5	10.5	11.2	11.2	7.8	11.1	11.1

Group.	691–700 A.D.	681–90	671–80	661–70	651–60	641–50	631–40	621–30	611–20	601–10	591–600	581–90	571–80	561–70	551–60	541–50	531–40	521–30	511–20	501–10
11. Total growth.......	1414.5	1129.0	1054.0	966.0	878.0	764.5	668.5	577.0	385.0	102.0	....	....	....	....	....	....	....	....	....	....
No. of measurements	69	60	59	53	47	42	32	26	14	3	....	....	....	....	....	....	....	....	....	....
Corrected growth...	380.0	296.5	274.0	248.0	223.0	192.0	167.0	139.3	88.3	23.4	....	....	....	....	....	....	....	....	....	....
12. Total growth.......	1581.5	1575.0	1527.0	1471.0	1493.5	1447.0	1376.5	1386.0	1599.0	1739.5	1459.5	1103.0	1107.0	1012.5	801.0	712.0	277.0	216.0	102.0	72.0
No. of measurements	58	....	....	....	....	....	....	....	....	58	52	43	36	30	26	23	12	10	5	3
Corrected growth...	485.0	475.0	456.0	435.0	437.5	418.0	391.0	386.0	436.0	464.0	385.0	298.0	289.0	261.0	204.0	174.0	69.3	52.7	24.9	16.8
13. Total growth.......	958.5	950.5	967.0	986.5	988.5	991.0	1024.0	951.0	1005.0	1000.0	1016.0	984.0	1032.5	984.0	944.5	1060.0	1054.0	1032.5	1033.0	1031.0
No. of measurements	49	....	....	47	48	....	....	....	....	....	....	....	....	....	....	....	....	....	....	48
Corrected growth...	334.0	328.0	331.0	335.0	331.0	329.0	336.0	309.0	324.0	321.0	321.0	308.0	320.0	301.0	286.0	318.0	312.0	302.0	298.0	291.0
14. Total growth.......	888.0	918.5	958.5	938.0	946.0	957.5	998.0	1056.0	1132.5	1124.0	1135.0	1130.5	1160.5	1072.0	1041.5	1132.0	1150.0	1108.0	1170.0	1156.5
No. of measurements	51	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	348.0	355.0	366.0	354.0	354.0	354.0	365.0	382.0	406.0	399.0	398.0	392.0	398.0	365.0	350.0	378.0	380.0	362.0	378.0	370.0
15. Total growth.......	586.5	607.0	590.5	644.5	605.0	584.5	626.0	652.0	733.5	696.0	710.0	778.0	799.5	745.0	774.5	813.0	738.0	779.0	821.0	817.5
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	265.0	271.0	260.0	280.0	260.0	247.5	263.5	271.5	303.0	385.5	387.0	311.0	315.0	290.5	298.5	310.0	278.0	291.0	302.5	298.0
16. Total growth.......	385.0	389.5	401.0	406.5	432.5	421.5	428.0	426.5	440.0	459.0	483.0	472.0	458.0	477.5	491.0	496.0	471.0	490.0	491.5	485.0
No. of measurements	33	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	195.0	195.0	198.5	198.0	208.0	200.5	201.0	199.0	204.0	209.5	217.0	210.0	201.0	207.0	211.0	211.0	199.0	205.0	203.0	199.5
17. Total growth.......	419.0	443.5	450.5	443.5	433.0	463.0	474.0	410.5	501.0	499.5	511.0	651.5	530.0	543.5	531.5	557.0	564.0	594.0	637.0	635.0
No. of measurements	47	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	250.0	261.0	261.0	253.0	244.0	258.0	261.0	222.0	268.0	264.0	266.0	284.0	269.0	274.0	264.0	272.0	274.0	285.0	302.0	299.0
18. Total growth.......	263.5	271.0	261.5	260.5	261.0	266.0	268.0	269.0	266.0	268.0	282.0	321.0	313.0	344.0	298.5	294.0	308.5	336.0	336.0	325.0
No. of measurements	30	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	179.0	182.0	174.0	171.0	169.0	170.0	169.0	167.0	164.0	163.0	159.0	189.0	182.0	197.0	169.0	165.0	170.0	183.0	181.0	172.0
19. Total growth.......	189.0	211.0	207.5	196.0	197.5	200.5	210.5	221.5	221.5	213.5	225.5	228.0	218.0	207.5	225.0	227.0	241.0	257.0	240.0	230.0
No. of measurements	25	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	145.0	161.0	157.5	148.0	148.0	149.0	156.0	163.0	161.5	154.0	161.0	161.0	153.0	144.0	154.0	154.0	162.0	170.0	157.0	148.0
20. Total growth.......	396.0	413.0	416.0	402.5	391.0	374.5	416.0	428.5	443.5	428.5	423.5	441.0	413.0	426.0	429.5	477.5	483.5	501.5	475.5	457.5
No. of measurements	49	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	321.0	334.0	334.0	322.0	311.0	296.0	328.0	336.0	346.0	323.0	326.0	339.0	316.0	324.0	326.0	358.0	358.0	368.0	346.0	330.0
21. Total growth.......	110.5	117.0	117.5	112.0	117.0	111.0	112.5	138.5	115.0	115.5	109.5	115.0	119.0	121.0	127.0	127.5	124.5	122.5	124.0	132.5
No. of measurements	17	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	94.0	99.0	99.0	94.0	97.5	92.5	93.5	114.5	95.0	95.0	89.5	93.5	96.5	97.5	102.0	102.0	99.0	97.0	98.0	104.0
22. Total growth.......	166.0	161.5	165.5	161.5	163.5	162.0	161.5	159.5	175.0	172.0	161.0	174.0	166.5	171.0	160.0	173.5	173.5	185.5	175.0	186.5
No. of measurements	24	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	153.0	148.0	151.0	147.0	148.5	146.5	146.5	143.0	156.0	153.0	142.5	153.0	146.0	149.0	139.0	150.0	149.5	159.0	149.0	158.5
23. Total growth.......	70.5	71.5	72.0	66.5	64.0	74.0	69.5	68.5	56.0	74.0	79.5	73.5	77.0	68.5	72.5	75.5	72.5	72.0	65.5	69.5
No. of measurements	11	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	68.0	68.8	69.0	63.5	61.0	70.2	65.7	64.5	52.5	69.2	74.0	68.3	71.3	63.0	66.7	69.0	66.0	65.2	59.0	62.5
24. Total growth.......	9.5	7.0	9.0	9.5	8.0	8.5	9.5	11.5	0.0	8.5	13.0	13.0	14.0	12.0	13.0	14.5	13.0	8.5	10.5	12.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	9.4	6.9	8.9	9.4	7.9	8.3	9.3	11.3	8.8	7.8	12.6	12.6	13.5	11.5	12.5	13.8	12.4	8.0	9.9	11.3
25. Total growth.......	20.5	23.0	26.5	27.0	26.5	23.5	28.5	26.5	26.5	28.5	30.5	35.0	33.5	25.0	26.0	26.0	24.0	25.5	26.0	28.0
No. of measurements	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	21.0	23.4	26.8	27.3	26.8	23.7	28.7	26.7	26.7	28.7	30.6	35.1	33.5	24.9	25.8	25.8	23.8	25.2	25.6	27.5
26. Total growth.......	28.5	26.5	30.5	31.0	33.5	31.0	33.0	29.5	33.0	32.5	25.0	33.5	38.0	38.0	28.5	26.0	32.0	30.0	30.5	26.0
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	29.9	27.8	31.9	32.4	35.0	32.4	34.4	30.7	34.3	33.8	25.9	34.7	39.3	39.3	29.4	26.8	32.9	30.8	31.3	26.7
27. Total growth.......	14.5	10.5	10.5	11.0	11.0	15.0	13.0	14.0	10.5	10.5	11.5	14.5	14.0	10.0	12.0	11.0	10.5	12.0	12.5	11.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	15.2	11.1	11.1	11.6	11.6	15.8	13.7	14.7	11.0	11.0	12.1	15.2	14.6	10.5	12.6	11.5	10.4	12.5	13.0	11.5
28 Total growth.....	5.5	5.0	5.5	5.0	6.0	6.5	6.0	7.0	7.0	5.5	6.0	6.0	5.5	5.0	6.0	5.0	5.0	4.5	5.5	5.5
& No. of meas'ments	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
29. Corrected growth.	6.0	5.5	6.0	5.5	6.5	7.1	6.5	7.6	7.6	5.9	6.5	6.5	5.9	5.4	6.5	5.4	5.4	4.8	5.9	5.9
30. Total growth.......	8.5	9.0	9.6	7.5	9.0	7.0	9.0	9.0	8.5	8.5	8.0	10.0	10.5	8.5	7.5	9.0	13.0	11.6	10.0	12.5
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	9.3	9.8	10.3	8.2	9.8	7.5	9.8	9.8	9.2	9.2	8.6	10.8	11.3	9.1	8.1	7.6	13.9	12.3	10.7	13.3
31. Total growth.......	10.5	10.0	10.5	10.0	10.0	10.0	11.0	10.0	11.5	8.5	8.5	9.5	7.5	10.5	10.0	9.0	7.0	8.0	8.5	7.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth...	11.7	11.1	11.7	11.1	11.1	11.0	12.0	11.0	12.7	9.3	9.3	10.5	8.2	11.5	10.9	9.8	7.6	8.7	9.2	8.1

Group.	491–500 A.D.	481–90	471–80	461–70	451–60	441–50	431–40	421–30	411–20	401–10	391–400	381–90	371–80	361–70	351–60	341–50	331–40	321–30	311–20	301–10
13. Total growth..	1005.0	1006.5	970.0	943.5	898.0	801.0	408.0	336.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
No. of measurements	46	44	44	42	37	31	17	12	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth ..	278.0	273.0	256.0	249.0	234.0	199.0	101.5	79.6	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14. Total growth....	1122.0	1136.0	1149.0	996.5	962.0	886.5	933.0	1000.0	912.0	965.5	923.0	767.0	749 0	596.5	490.5	463.0	282.5	357.5	229.0	.....
No. of measurements	51	.....	.....	51	50	.....	.....	.....	.....	60	48	44	36	26	21	17	11	11	9	.....
Corrected growth.	356.0	350.0	357.0	307.0	293.0	266.0	274.0	289.0	250.0	267.0	253.0	208.0	200.0	157.5	129.5	122.5	74.7	91.0	55.0	.....
15. Total growth	845.5	860.0	839.5	883.5	867.0	923.5	894.5	897.0	871.0	878.0	890.5	988.0	951.5	966.0	960.0	931.0	924 0	896.5	809.0	857.0
No. of measurements	47	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	47	45	44	42
Corrected growth	306.0	307.0	297 0	308.0	300.0	317.0	302.5	302.0	290.5	290.0	390.5	319.0	304.5	306.0	301.5	289.0	282.0	268.0	242.5	252 5
16. Total growth .	506.0	532.0	558.5	514 0	566.0	569.5	568.5	593.0	560.0	558.5	561.0	561.5	604.5	625.0	596.0	655.5	674.5	641.5	631.5	665.5
No. of measurements	33	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	33
Corrected growth...	204.5	212.0	220.0	200.0	218.0	217.5	214.5	221.5	207.5	213.5	203.0	201.0	214.0	219.0	207.0	225.0	230.0	216.0	211.0	220.5
17. Total growth.......	630.5	637.0	662.0	673.0	649.0	680.5	733.0	777.0	748.0	763.5	717.0	753.0	786.5	838 0	863.0	814.0	905.5	979.5	971.5	1032.5
No. of measurements	47	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth ..	293.0	292.0	300.0	300.0	286.0	299.0	317.0	334.0	318.0	321.0	298.0	319.0	351.0	336.0	342.0	319.0	352 0	375.0	370.0	389.0
18. Total growth.......	333.5	336.0	381.5	355.5	358.0	394.0	391.0	387.5	412.5	428.5	433.5	460.5	442.5	424.5	450.5	423.5	452.5	427.0	425.5	472.5
No. of measurements	30	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	175.0	174 0	195.0	179 0	179.0	194.5	192.0	187.0	198.0	203.0	202.0	211.5	201.0	191.0	201.0	186.5	197 5	185.0	182.0	200.0
19. Total growth.......	240.5	249.0	234.5	244 0	231.5	230.5	239 0	259.5	279.5	269.5	277.0	283.0	296.5	243.5	291.5	294.5	285.5	281.5	281.5	288.5
No. of measurements	25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	153.0	156.5	145.5	149 0	139.0	137.0	140.0	150.0	159 5	151.5	154 0	155.5	161.0	130.0	154.0	154.0	147.0	143.5	142.0	144.5
20. Total growth.......	478.5	458.0	479.0	498.5	511.0	485.0	495.0	500.5	507.5	516.5	554 0	581 5	604.5	628.0	613.5	619.0	645.5	634.5	655.5	634.0
No. of measurements	49	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth..	342.0	324 0	335 0	345.0	349.0	327.0	328.0	328.0	329.0	330.0	349.0	361.0	370.0	380.0	366.0	365.0	375.0	363.0	371.0	355.0
21. Total growth.	125.0	136.0	133.0	129.5	133.5	143.0	140.0	158.0	142.5	161.5	155.5	166.0	167.5	178.5	171.5	173.0	174.5	178.0	177.0	186.0
No. of measurements	17	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth .	97.0	105.0	102.0	98.0	100.0	106 0	103.0	115.0	102.5	115.0	110.0	115.5	115.0	121.0	114.5	114.5	114 0	114 5	112.0	116.0
22. Total growth.......	185.0	183.5	190.5	186.5	181.0	186.0	199.0	195.5	196.5	201.0	213.0	207.5	207.5	219.0	211.0	213.0	215.0	206.0	203.5	215.5
No. of measurements	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	156.0	154.0	159.5	155.5	150.0	153.5	163.5	160.0	160.0	162.5	171.0	166.0	165.0	173.5	166.0	166.0	166.0	157.5	154.0	162.0
23. Total growth.......	72.0	74.0	74.5	79.0	85.0	79.0	80.0	79.5	83.0	78.0	83.5	79.0	81.0	81.5	91.0	84.5	83.0	77.0	78.0	87.5
No. of measurements	11	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth ..	64.3	66.0	66.0	69.6	74.6	69.0	69.6	69.0	71.5	67.0	71.3	67.2	68.5	68.6	76 2	70.5	68.7	63.5	64.0	71.5
24. Total growth.......	13.5	14.0	15.0	16.0	16 0	14.0	12.5	13.0	13.5	12.0	14.5	16.0	15.5	13.0	11.0	12.0	11.5	12.0	11.0	11.5
No. of measurements	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	12.6	13.0	13.9	14.8	14.7	12.8	11.4	11.8	12.3	10.8	13.0	14.3	13.8	11.5	9.6	10.5	10.1	10.5	9 6	9.9
25. Total growth.......	20.0	20.5	24.0	29.5	24.5	25.5	25.5	23.0	24.5	34.0	36.0	30.0	26.5	26.5	25.5	20.0	28.0	24.5	23.5	23.0
No. of measurements	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	19.6	20.0	23.4	28.7	23.7	24.6	24.5	22.0	23.4	32 4	34.2	28.4	25.0	24.9	23.8	18.5	25.8	22.6	21.5	20.9
26. Total growth.......	27.5	32.0	34.5	34.5	31.5	31.0	35.5	35.5	36.5	34.0	26.5	29.5	32.0	28.5	32.5	28.5	28.5	28.5	34.5	33.0
No. of measurements	5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	28.1	32.7	35.2	35.1	32.0	31.5	30.0	36.0	36.9	34.3	26.8	29.5	32.0	28.4	32.3	28.3	28.2	28.2	33.9	32.4
27. Total growth.......	14.5	14.0	12.0	13.5	16.0	16.0	15.0	16.0	12.0	16.0	15.5	16.5	18.5	18.0	19.5	16.0	13.5	13.0	15.5	19.0
No. of measurements	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	15.0	14.5	12.4	14.0	16.5	16.5	15.4	16.4	12.3	16.3	15.8	16.8	18.9	18 3	19.8	16.2	13.7	13.2	15.7	19.1
28 Total growth.....	5.5	5.5	5.0	5.5	5.0	5.0	4.5	5.0	3.5	4.0	5.5	5.0	5.0	4.5	4.0	3.5	3.5	4.0	4.0	4.5
& No. of meas'ments	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
29. Corrected growth.	5.9	5.9	5.3	5.9	5.3	5.3	4.8	5.3	3.7	4.2	5.8	5.3	5.3	4.7	4.2	3.7	3.7	4.2	4.2	4.7
30. Total growth.......	12.5	11.0	12.0	11.0	8.5	9.0	8.5	8.5	8.5	7.5	6.0	6.0	6.0	6.5	7.5	11.0	8.0	7.0	7.0	5.0
No. of measurements	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	13.3	11.7	12.8	11.7	9.0	9.5	9.0	9.0	9.0	7.9	6.3	6.3	6.3	6.8	7.9	11 .5	8.4	7.3	7.3	5.2
31. Total growth.......	7.0	7.0	7.0	7.0	9.0	9.0	10.0	8.0	8.0	9.0	9 0	9.5	10.5	10.0	9.0	10.5	11.0	17.0	12.5	11.5
No. of measurements	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	7.6	7.6	7.6	7.6	9.7	9.7	10.8	8.6	8.6	9.6	9.6	10.2	11.2	10.7	9.6	11.2	11.7	18.0	13.2	12.2

Group.	291–300 A. D.	281–90	271–80	261–70	251–60	241–50	231–40	221–30	211–20	201–10	191–200	181–90	171–80	161–70	151–60	141–50	131–40	121–30	111–20	101–10
15. Total growth.......	947.5	838.5	808 0	783.5	661.0	667.5	474.0	387.5	369.5	162.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
No. of measurements	42	40	34	32	31	28	21	14	11	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	273.0	249.5	228.0	219.0	180.0	179.5	125.0	100.5	91.2	40.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16. Total growth.......	626.5	601.5	678.5	609.5	569.5	546.5	537.5	577.0	555.0	602 5	675.5	396.0	357.5	303.0	181 0	189.0	103.0	110.0	134.0	.....
No. of measurements	33	.....	.....	.....	33	32	31	31	29	29	27	19	17	15	12	10	5	4	4	.....
Corrected growth...	205.0	195.0	217.0	193.0	177.2	167.5	163.5	172.0	164.0	174.0	190.5	113.5	101.0	84.5	49.8	49.8	28.3	29.0	33.8	.....
17. Total growth.......	1055.5	1115.5	1095.0	1215.5	1180.0	1195.5	1250.5	1256.0	1250.5	1237.0	1155.5	1054.0	1012.5	1019.0	1029.0	1059.0	963.5	986.5	889.0	885.5
No. of measurements	47	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	47	45	43	42
Corrected growth...	392.0	410.0	398.0	437.0	420.0	422.0	437.0	435.0	429.0	420.0	388.0	351.0	334.0	332.0	332.0	333.0	300.0	305.0	270.0	266.0
18. Total growth.......	461.0	452.0	453.0	476 0	504.5	512.5	514.0	514.0	533.5	552.0	549.0	616.0	604.5	636.0	640.0	632.5	655.0	616.0	608.0	570.5
No. of measuremeots	30	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	193.0	187.0	185.0	192.0	201.0	203.0	201.0	198.0	204.0	209.0	206.0	228.0	222.0	231.0	230.0	225.0	231.0	215.0	210.5	195.0
19. Total growth.......	292.5	303.5	324.0	325.5	358.5	348.0	364.5	377.5	359.0	373.0	404.5	363.5	379.0	396.5	445.0	481.5	433.0	445.5	444.0	469.0
No. of measurements	25	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	145.0	149.0	156.0	155.0	169.0	162.0	167.5	172.0	161.5	166.5	197.0	158.5	164.0	169.0	188.0	201.0	178.0	186.0	179.5	187.5
20. Total growth.......	624.5	602.5	617.5	620.5	654.5	679.0	682.0	726.0	673.5	688.0	683.5	706.5	685.0	728.0	715.0	735.0	776.5	782.0	802.0	821.5
No. of measuremeots	49	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	344.0	328.0	333.0	330.0	344.0	352.0	352.0	371.0	339.0	343.0	336.0	343.0	328.0	343 0	333.0	340 0	357.0	356.0	362.0	368.0
21. Total growth.......	167.0	186.5	190.5	212.5	205.5	200.0	210.5	200.0	202.0	204.0	200.0	205.5	199.5	195.0	219.5	215.5	230.0	242.0	231.5	217.5
No. of measurements	17	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	103.0	113.5	114.5	126.0	120.0	115.0	120.5	112.0	112.0	112.0	108.0	110.0	106.0	102.0	214.0	100.5	117.0	121.0	114.5	106.0
22. Total growth.......	216.0	235.5	231.0	229.5	231 5	237.0	232.0	236.0	245.0	231.0	238.5	214.5	230.0	227 0	238.0	232.5	245.0	242.0	248.0	247.0
No. of measurements	24	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	160.0	173.0	168.0	165.0	165.0	166.0	160.5	161 0	165.0	154.0	156.5	139.0	146.0	142.5	147.5	142.0	148.0	144.0	146.0	143.5
23. Total growth.......	87.0	83.0	79.5	81.0	85.5	92.5	91.0	92.5	91.0	84.5	81.0	88.5	91.0	95.0	96 0	86.5	91.5	82.0	95.0	109.0
No. of measurements	11	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	70.8	67.0	64.0	64.5	67.5	72.5	70.5	71.0	69.0	63.5	60.3	65.2	66.2	68.3	68.0	60.5	63.3	56.0	64.0	72.5
24. Total growth.......	10.0	13.0	13.0	11.5	13.0	16.0	16.0	17.5	16.5	15.5	12.0	15.0	14.0	15.5	15.5	21.0	20.5	14.5	18.5	16.5
No. of measurements	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	8.6	11.1	11 1	9.7	11.0	13.4	13.4	14.6	13.7	12.8	9.8	12.2	11.3	12.5	12.4	16.6	16.1	11.3	14.2	12.6
25. Total growth.......	21.5	27.5	24 0	26.0	26.0	28.5	32.5	35.0	33.5	30.5	32.0	31.5	29.0	34.5	31.5	33.0	32.0	38.5	33.5	31.5
No. of measurements	4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	19.5	24.8	21.6	23.2	23.2	25.2	28.6	30.7	29.3	26.5	27.8	27.2	24 9	29.6	26.8	27.9	27.0	32.3	27.9	26.1
26. Total growth.......	32.5	32.5	36.5	38.5	39.0	37.5	35.0	35.5	42.5	43.0	40.5	38.0	35.5	30.5	28.0	29.0	25.5	27.5	27.5	32.0
No. of measurements	5	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	31.8	31.7	35.5	37.3	38.6	36.1	33.6	33.9	40.4	40 8	38.2	35.7	33.1	28.4	25.9	26.7	23.3	25.1	24.9	28.9
27. Total growth.......	16.0	15.5	20.0	18.5	16 0	16.0	16.0	19.5	17.0	16.5	14.0	16.0	15.5	15.5	17.5	11.5	12.0	14.0	8.5	11.5
No. of measurements	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	16.0	15.5	20.0	18.5	15.9	15.9	15.8	19.3	16.7	16.2	13.6	15.5	15.0	15.0	16.8	11.0	11.5	13.3	8.0	10.8
28 & 29. Total growth.....	4.0	4.0	4.0	7.0	9.0	8.5	8.5	9.0	9.5	8.0	7.5	8.5	8.5	8.5	8.5	6.0	7.0	8.0	7.5	7.5
No. of meas'ments	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth.	4 2	4 2	4 2	7.3	9.3	8.8	8.8	9.3	9.8	8.3	7.7	8.8	8.7	8.7	8.7	6.1	7.2	8.2	7 7	7.6
30. Total growth.......	7.0	7.0	7 0	8.0	6.0	4.0	5.5	7.0	8.0	8.0	9.0	6.0	7.0	9.0	6.5	6.5	5.5	7 5	8.0	9.0
No. of measurements	1	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	7.3	7.3	7.3	8.3	6.2	4.1	5.7	7.3	8.3	8.3	9.3	6.2	7.2	9.2	6.6	6.6	5.6	7.7	8.1	9.1
31. Total growth.......	8.5	9.0	11.5	12.0	11.5	12.5	9.5	7.5	10.0	10.0	10.0	11.5	11.5	10.0	11.0	12.0	8.5	8.5	8.0	11.5
No. of measurements	2	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
Corrected growth...	9.0	8.5	12.1	12.6	12.1	13.1	10.0	7.9	10.5	10.5	10.4	12.0	12.0	10.4	11.4	12.5	8.8	8.8	8 3	11.9

Group.	91–100 A.D.	81–90	71–80	61–70	51–60	41–50	31–40	21–30	11–20	A.D. 1–10	10–1 B.C.	20–11	30–21	40–31	50–41	60–51	70–61	80–71	90–81	100–91
17. Total growth	692.5	624.5	741.0	733.5	485.0	505.0	253.5	247.0	122.0											
No. of measurements	36	34	34	30	25	23	11	7	4											
Corrected growth	203.0	183.5	213.0	206.0	136.0	136.0	68.2	65.0	31.1											
18. Total growth	573.5	596.5	613.5	580.5	593.5	608.0	597.5	550.5	579.0	574.5	568.5	504.5	264.0	219.5	134.5	135.0	146.5	106.5	69.0	
No. of measurements	30										30	24	14	11	7	7	7	5	2	
Corrected growth	194.5	200.5	203.0	190.0	191.5	193.5	186 0	168.5	173.0	167.5	162.0	144.0	77.0	64.0	39.3	38.5	40.1	27.8	18	
19. Total growth	458.0	460.0	450.0	471.0	526.5	482.5	479.0	506.5	529.0	544.0	528.0	514.5	478.5	461.0	486.0	484.5	476.5	466.0	457.5	420.0
No. of measurements	25																			25
Corrected growth	181.0	180.0	173.5	180.0	199.0	180.0	177.5	186.0	193.0	196 0	188.5	181.5	167.0	159.2	167.0	164.0	160.0	154 0	148.5	134.0
20. Total growth	843.0	873.5	1008.5	959.5	1018.5	1018.5	1100.0	1002.5	1066.5	1060.5	1031.0	1050.5	1061.0	1035.5	1021.5	943 0	937.0	994.5	923.5	966.5
No. of measurements	49																			
Corrected growth	371.0	378.0	431.0	406 0	428.0	423.0	452.0	407.0	428.0	422.0	405.0	410.0	408.0	395 0	387.0	352.0	347.0	365.0	335.0	348.0
21. Total growth	237.5	243.0	276.5	293.0	278.0	289.5	257.0	271.5	263.0	263.0	274.0	303.0	331.0	320.5	354.5	346.0	332.0	322.5	324.5	322.0
No. of measurements	17																			
Corrected growth	114.5	115.5	130.5	137.0	129.0	128.5	117.0	122.0	116.0	115.0	118.5	130.0	140.5	135.0	147.0	142.5	134.5	129.0	129.0	126.0
22. Total growth	255.5	277.0	276.0	280.0	297.0	326.0	291.5	297.0	317.0	288.5	291.0	295.5	291.0	302.0	308.5	306 5	320.0	345.5	376.5	368.0
No. of measurements	24																			
Corrected growth	146.0	157.0	154.0	155.0	162.0	176.0	156.0	157.5	166.0	149 5	149.0	149.0	145.0	148.0	149.5	147.5	152.0	164.0	176.5	170.5
23. Total growth	100.5	108.5	123.5	125.0	113.5	123.5	114 0	120.5	121.5	118.0	118.0	117.0	125.0	117.0	111.5	118.0	121.0	120.0	134.5	153.0
No. of measurements	11																			
Corrected growth	65.7	70.0	78.8	78.5	70.5	75.7	68.9	71.7	71.5	68.5	67.6	66.2	70.0	64.7	61.0	63.8	64.7	63.5	70.5	79.3
24. Total growth	16.0	17.5	16.5	14.5	13.5	15.5	13.5	17.0	14.5	18 5	17.5	25.5	17.0	22 5	25.5	22.5	22.5	24.0	22.5	21.5
No. of measurements	2																			
Corrected growth	12.1	13.1	12 2	10 6	9.6	11.0	9 5	11.8	9.9	12.4	11.6	16 6	10.9	14.3	16.0	13.9	13.8	14.5	13.4	12.6
25. Total growth	31.0	34 0	32.0	32.5	36.0	39.0	35.5	36.5	35.5	33.0	30.5	33.0	38 0	36.0	34.5	33.0	35.5	27.0	25.5	26.5
No. of measurements	4																			
Corrected growth	25.6	27.9	26.0	26.2	28.8	30.8	27.7	28.2	27.2	25.0	22.9	24.4	27.8	25.9	24.5	23.2	24.6	18.5	17.2	17.6
26. Total growth	33.5	27.5	34.0	29.0	33.5	32 0	33.5	31.0	34 5	33.0	39.5	30.0	30.0	29.0	33 0	30.5	34.0	31.0	39.5	41.5
No. of measurements	5																			
Corrected growth	30.2	24.7	30.3	25.8	29.7	28.2	29.4	27.0	30.0	28.6	25.4	25.7	25.6	24.6	27.8	25.6	28.4	25.7	32.5	33.7
27. Total growth	13.5	11 5	14.0	14 5	13 5	15.5	14.5	14.5	11.5	12.0	14.5	16.0	15.5	17.0	15.0	14.5	15.0	13.5	16.0	17.5
No. of measurements	2																			
Corrected growth	12.7	10.7	13.0	13.4	12.4	14.2	13.2	13.1	10.4	10.8	13.0	14.3	13.8	15.0	13.2	12.7	13.1	11. 7	13.8	15.1
28 & 29. Total growth	6.5	5.5	6 0	5 5	5.5	4.5	4.5	5.0	5.0	6.0	6.5	6.0	8.5	8.0	8.5	7.5	7.0	7.5	6.0	5.5
28 & 29. No. of meas'ments	1																			
28 & 29. Corrected growth	6.6	5.6	6.1	5.5	5.5	4.5	4.5	5.0	5.0	6.0	6.5	5.9	8.4	7.8	8.3	7.3	6.8	7.3	5.8	5.3
30. Total growth	8.5	7.5	9.0	8.5	8 0	10.0	11.0	12.0	10.0	7.5	7.5	10.0	10.5	10 0	9.0	9.0	9.0	8.0	7.5	6.5
No. of measurements	1																			
Corrected growth	8.6	7.6	9.0	8 5	8 0	10.0	11 0	12.0	10.0	7.5	7.4	9.9	10.3	9.8	8.8	8.8	8.7	7 7	7.2	6.2
31. Total growth	12.5	9.5	10.5	11.5	10.5	10.5	9.0	9.5	8.0	10 0	10.5	13.0	12.5	12.5	10.5	14.0	10.5	13.5	15.5	12.0
No. of measurements	2																			
Corrected growth	12 9	9.8	10.8	11.9	10.8	10.8	9.2	9.7	8.2	10.2	10.7	13.2	12 7	12.7	10.6	14.0	10.5	13 5	15.5	12.0

Group.	110–101 B.C.	120–11	130–21	140–31	150–41	160–51	170–61	180–71	190–81	200–191	210–201	220–11	230–21	240–31	250–41	260–51	270–61	280–71	290–81	300–291
19. Total growth	435.0	392.0	290.5	289.0	260.5	247.5	207.5	203.5	137.5											
No. of measurements	23	22	21	19	17	15	13	12	7											
Corrected growth	138.0	90.3	89.0	87.5	77.8	72.3	59.5	55.2	36.7											
20. Total growth	953.5	890 5	875.0	764.0	775.0	705.5	632.0	650.5	640.5	660.5	667.5	456.5	469.0	445.5	485 0	374.5	314.5	179.5	128.0	
No. of measurements	49										49	43	36	34	30	22	18	7	4	
Corrected growth	339.0	314.0	305.0	263.0	265.0	238.0	209.0	211.0	204.0	205 0	205.0	137.0	142.5	133.5	141.0	109.0	87.0	49.5	34.8	
21. Total growth	326.5	314.0	338.5	357.5	346.5	353.5	449.0	410.0	373.5	301.0	408.0	341.0	320.5	354.5	325.0	292.0	253.5	192 5	168.5	169.0
No. of measurements	17													17	15	15	14	12	12	12
Corrected growth	128.0	124 0	130.5	136.5	131.0	132.0	166.0	150.0	135.5	108.0	145.0	120.0	113.0	119.0	109.0	96.5	83.0	65.0	55.7	55.0
22. Total growth	362.5	351.5	381.0	394.0	394.5	394.5	409.0	429.0	424.0	464.0	464.0	481.5	491.0	540.5	598 5	634.5	584.5	570.5	547.5	537.5
No. of measurements	24																			
Corrected growth	166.0	158.5	171.0	174.0	172.0	170.0	175.0	181.0	176.5	192.0	189.5	195.0	196.5	214.0	235.0	246.0	225.0	217.0	206.0	203.0
23. Total growth	141.5	161.0	159.5	151.5	148.5	150.0	167.5	164.5	178.0	170.0	156.0	185.0	187.0	176.0	174.5	207.0	243.0	215.0	249.0	240.5
No. of measurements	11																			
Corrected growth	72.2	81.3	79.5	74.4	72.6	72.6	80.5	78 2	83.5	78.8	71.5	83.5	83.5	77.5	76.2	89.5	104.0	91.0	104.5	100.0
24. Total growth	18.5	19.5	23.5	17.5	15.5	21.5	22.0	23.0	24.5	24.0	24.0	24.5	34 0	33.0	33.5	33.0	32.5	36.5	36.0	27.5
No. of measurements	2																			
Corrected growth	10.7	11.2	13.4	9.8	8.6	11.8	11 9	12.3	13.0	12.6	12 4	12.5	17.2	16.5	16.5	16.2	15.8	17.1	17.1	12.9
25. Total growth	25.5	28.0	27.0	30.5	33.5	38.0	39.5	44.5	37.0	43.5	43.5	44.0	41.0	49.0	51.5	51.0	53.0	56.0	64.0	69.0
No. of measurements	4																			
Corrected growth	16.7	18.1	17.3	19 4	20.8	23.3	23.9	26.6	21 9	25.4	25 0	25.0	23 0	27.2	28.4	27.8	28.6	30.0	33.6	35.8
26. Total growth	30.0	32.5	32.5	36.5	40.0	41.5	38.0	39.5	41.0	43.5	47.5	48.5	49.0	38.5	52.0	48.0	47.0	50.0	52.0	47.5
No. of measurements	5																			
Corrected growth	24.2	26.0	25.7	28.5	31.0	31.8	28.5	29 3	30.0	31.4	33.7	34.0	33.9	26.3	35.0	31.9	30.8	32.3	33.1	29.8
27. Total growth	18.0	18.5	15.5	14.0	13.5	15.0	16.5	16.0	14.0	14.0	12.0	14.5	17.0	17.5	22.0	16.5	18.5	24.0	20.5	17.5
No. of measurements	2																			
Corrected growth	15.4	15.8	13.1	11.8	11.3	12.5	13.7	13.3	11.5	11.4	9.7	11.6	13.4	13.7	17.1	12.6	14.0	18.0	15.2	12.8
28 & 29. Total growth	6.0	5.0	5.0	5.0	5.0	8.5	5.5	5.5	6.0	6.5	6.0	5.0	4.0	6.0	5.5	6.5	9.0	10.5	11.5	13.0
28 & 29. No. of measurements	1																			
28 & 29. Corrected growth	5.8	4.8	4.8	4.7	4.7	8.0	5.1	5.1	5.5	6.0	5.5	4.6	3.6	5.4	4.5	5.8	8.0	9.3	10.2	11.5
30. Total growth	6.5	7.0	7.5	5.5	7.0	8.0	5.5	8.0	10.0	8.5	10.0	8.0	8.5	9.0	9.0	8.5	8.5	8.0	8.0	7.5
No. of measurements	1																			
Corrected growth	6.2	6 7	7.1	5.2	6.6	7.5	5.1	7.4	9.2	7.8	9.1	7.3	7.7	8.1	8.1	7.6	7.5	7.1	7.0	6.6
31. Total growth	13.5	14.5	17.0	15.5	17.5	13.0	12.0	11.0	12.0	14.0	11.5	10.0	11.5	11.0	11.5	9.5	11.5	13.5	14 5	15.0
No. of measurements	2																			
Corrected growth	13.5	14.5	17.0	15.3	17.2	12 8	11.7	10.7	11.7	13.6	11.1	9.6	11.0	10.5	11.0	9.0	10.8	12.7	13.6	14.0

Group.	310–301 B.C.	320–11	330–21	340–31	350–41	360–51	370–61	380–71	390–81	400–391	410–401	420–11	430–21	440–31	450–41	460–51	470–61	480–71	490–81	500–491
21. Total growth	145.5	144.0	153.5	97.5	75.0	81.0	106.0	....	....	....	....	....	....	....	....	....	....	....	....	....
No. of measurements	12	11	11	7	7	5	5	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	46.0	44.7	46.5	29.7	22.2	24.4	29.3	....	....	....	....	....	....	....	....	....	....	....	....	....
22. Total growth	552.5	530.0	529.0	534.5	543.5	583.5	605.5	644.5	563.5	616.5	595.5	491.0	422.0	337.0	351.5	318.0	154.5	131.5	....	....
No. of measurements	24	....	....	....	....	....	....	....	....	24	23	19	15	13	13	12	8	4	....	....
Corrected growth	207.0	196.0	193.5	194.0	195.0	207.0	212.0	222.0	190.5	204.0	197.0	161.0	137.0	106.5	109.0	93.2	44.6	37.0	....	....
23. Total growth	219.5	223.0	228.5	256.0	228.0	198.0	190.0	218.0	228.0	239.5	240.5	185.0	184.0	187.0	169.5	165.5	146.5	101.0	108.5	149.0
No. of measurements	11	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	11	9	9	9
Corrected growth	90.0	90.2	92.0	102.0	89.8	77.2	73.4	83.2	86.5	89.5	89.3	67.8	67.0	67.3	60.0	57.5	50.1	35.2	37.1	50.0
24. Total growth	31.0	32.0	36.0	38.0	38.0	38.0	28.0	30.0	32.0	44.0	40.0	28.0	42.0	30.0	30.0	38.0	38.0	28.0	19.0	18.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	14.3	11.6	16.3	17.0	16.8	16.7	12.1	12.9	13.6	18.5	16.6	15.6	17.0	12.1	12.0	15.0	14.9	10.8	7.3	6.8
25. Total growth	68.0	52.5	51.5	43.0	47.5	56.0	62.5	57.0	47.0	49.0	56.0	61.0	58.5	53.5	41.0	41.5	47.0	51.5	64.0	61.5
No. of measurements	4	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	34.7	26.5	25.8	21.4	23.4	27.4	30.2	27.2	22.1	22.8	25.8	27.8	26.3	23.8	18.0	18.1	20.3	22.0	27.1	25.6
26. Total growth	56.0	58.0	64.5	65.0	68.0	73.0	66.0	77.0	78.0	80.5	88.0	83.5	71.5	95.0	101.0	90.0	97.0	97.5	93.5	100.0
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	34.8	35.6	39.0	38.8	40.2	42.6	38.0	43.8	44.1	45.0	48.6	45.6	38.6	50.5	53.0	46.7	49.7	49.5	47.1	49.9
27. Total growth	15.0	14.0	12.5	14.5	18.5	20.5	19.5	20.0	26.5	22.0	21.0	21.0	22.0	20.0	23.0	24.0	26.0	22.0	22.0	18.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	10.8	9.9	8.8	10.0	12.6	13.8	12.9	13.1	17.1	14.0	13.2	13.0	13.5	12.1	13.7	14.2	15.2	12.7	12.6	10.2
28 Total growth	10.0	11.5	13.5	10.0	7.0	5.5	6.0	7.0	7.5	6.0	7.0	8.0	7.5	9.0	9.5	10.5	10.5	9.0	11.0	13.0
& No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
29. Corrected growth	8.8	10.0	11.7	8.7	6.0	4.7	5.1	6.0	6.4	5.1	5.9	6.7	6.2	7.4	7.7	8.4	8.3	7.0	8.5	10.0
30. Total growth	7.0	8.5	9.0	12.0	12.0	10.5	11.0	8.0	11.0	14.9	15.0	17.0	18.0	19.0	17.0	16.0	14.0	14.5	12.0	11.5
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	6.1	7.4	7.8	10.3	10.3	9.0	9.4	6.8	9.3	11.8	12.5	14.1	14.8	15.5	13.6	12.7	11.0	11.3	9.2	8.7
31. Total growth	13.0	13.0	13.0	15.5	17.0	15.0	15.5	15.5	15.0	13.0	12.0	14.0	11.5	16.0	25.5	15.0	13.0	17.0	18.5	12.5
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	12.0	12.0	11.9	14.1	15.4	13.6	13.9	13.9	13.4	11.5	10.6	12.3	12.7	14.0	22.1	13.0	11.2	14.6	15.8	10.7

Group.	510–501 B.C.	520–11	530–21	540–31	550–41	560–51	570–61	580–71	590–81	600–591	610–601	620–11	630–21	640–31	650–41	660–51	670–61	680–71	690–81	700–691
23. Total growth	113.0	123.0	77.5	80.5	90.0	109.5	111.5	84.0	....	....	....	....	....	....	....	....	....	....	....	....
No. of measurements	7	7	5	5	5	5	5	4	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	38.0	40.3	26.0	26.4	28.9	34.2	43.4	24.0	....	....	....	....	....	....	....	....	....	....	....	....
24. Total growth	24.0	17.0	20.0	11.0	10.0	9.0	11.0	12.0	9.0	11.0	16.0	20.0	42.0	....	....	....	....	....	....	....
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	2	....	....	....	....	....	....	....
Corrected growth	9.0	6.3	7.4	4.0	3.6	3.2	3.8	4.1	3.0	3.6	5.1	6.1	12.2	....	....	....	....	....	....	....
25. Total growth	50.5	49.0	57.5	59.5	63.0	33.0	33.0	15.0	18.5	15.5	18.0	26.0	23.0	26.0	22.0	26.0	27.0	35.0	43.0	44.5
No. of measurements	4	....	....	....	4	2	....	....	....	....	....	....	....	....	....	....	....	....	....	2
Corrected growth	20.9	20.1	23.3	23.8	25.1	13.0	12.9	5.8	7.1	5.9	6.7	9.6	8.4	9.3	7.7	9.0	9.1	11.5	13.7	13.8
26. Total growth	86.5	85.5	105.0	84.0	90.0	95.5	96.0	110.0	105.5	88.0	104.5	106.5	100.0	92.0	100.0	109.0	126.0	122.0	108.0	84.0
No. of measurements	5	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	42.9	41.8	50.8	40.0	42.3	44.4	44.3	50.2	47.6	39.3	46.0	46.7	43.2	39.4	42.3	45.6	52.3	50.1	43.9	33.9
27. Total growth	17.0	20.0	18.0	13.0	22.0	15.0	18.0	19.0	22.0	16.0	19.0	19.0	18.0	24.0	20.0	18.0	25.0	17.0	19.0	14.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	9.5	11.0	9.8	7.0	11.7	7.9	9.3	9.7	11.2	8.1	9.5	9.4	8.8	11.7	9.5	8.5	11.7	7.8	8.6	6.3
28 Total growth	12.0	14.0	16.0	15.5	13.5	12.5	12.6	12.0	12.0	9.5	10.5	10.5	13.5	13.0	13.0	12.0	15.0	14.0	12.0	18.0
& No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
29. Corrected growth	9.1	10.5	11.8	11.3	9.6	8.9	8.7	8.3	8.2	6.4	7.0	6.9	8.6	8.3	8.2	7.5	9.2	8.5	7.2	10.6
30. Total growth	15.0	13.0	10.0	9.0	8.0	11.0	12.0	15.0	15.0	14.5	12.0	12.0	12.5	15.0	19.0	14.0	16.0	15.0	13.0	14.0
No. of measurements	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	11.2	9.6	7.3	6.5	5.7	7.7	8.3	10.2	10.1	9.6	7.8	7.8	8.0	9.4	11.8	8.6	9.7	9.0	7.7	8.2
31. Total growth	12.5	17.0	20.0	19.0	20.0	15.5	14.0	20.0	11.5	13.0	12.0	15.0	17.0	16.5	13.5	14.0	14.5	21.0	19.0	18.0
No. of measurements	2	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Corrected growth	10.6	14.4	16.8	15.9	16.6	12.7	11.4	16.0	9.1	10.2	9.3	11.5	12.9	12.4	10.0	10.2	10.4	15.0	13.3	12.5

Group.	710–701 B. C.	720–11	730–21	740–31	750–41	760–51	770–61	780–71	790–81	800–791	810–801	820–11	830–21	840–31	850–41	860–51	870–61	880–71	890–81	900–891
25. Total growth	53.5																			
No. of measurements	2																			
Corrected growth	15.7																			
26. Total growth	79.5	71.0	80.5	87.5	94.5	83.0	81.0	83.0	84.0	55.0	67.5	91.5	98.0	110.5	67.0	51.0	57.0			
No. of measurements	5													5	3	3	3			
Corrected growth	31.7	28.2	31.5	33.8	36.2	31.5	30.4	23.3	23.2	19.6	23.6	31.2	32.7	30.8	21.9	16.0	17.0			
27. Total growth	20.0	13.0	11.0	17.0	14.0	25.0	17.0	18.0	38.0	40.0	24.0	30.0	26.0	18.0	15.0	24.0	27.0	28.0	26.0	26.0
No. of measurements	2																			
Corrected growth	8.8	5.7	4.7	7.3	5.9	10.5	7.1	7.4	15.5	16.1	9.5	11.9	10.3	7.0	5.7	9.1	10.1	10.3	9.5	9.3
28 Total growth	18.0	24.0	33.0	37.0	39.0	19.0	19.0	22.0	19.0	21.0	19.0	18.0	17.0	15.0	20.0	23.0	16.0	15.0	24.0	28.0
& No. of measurements	1																			
29. Corrected growth	10.5	13.8	18.8	20.9	21.8	10.5	10.4	11.9	10.2	11.0	9.2	9.2	8.7	7.5	10.0	11.4	7.8	7.3	11.4	13.2
30. Total growth	11.0	13.0	15.5	15.0	14.5	15.0	15.0	13.0	15.0	18.0	20.0	16.0	20.0	23.0	16.0	15.0	16.0	18.0	16.0	18.0
No. of measurements	1																			
Corrected growth	6.3	7.4	8.8	8.4	8.0	8.2	8.1	6.9	7.9	9.4	10.3	8.1	10.1	11.5	7.9	7.3	7.7	8.6	7.5	8.4
31. Total growth	19.0	17.0	14.0	16.0	19.0	14.5	16.0	20.5	18.0	16.0	17.0	20.0	19.0	24.0	24.0	27.0	21.0	25.0	16.0	21.5
No. of measurements	2																			
Corrected growth	13.0	11.4	9.3	9.8	12.2	8.9	10.1	12.7	11.0	9.7	10.1	11.8	11.1	13.8	13.7	15.3	11.8	12.7	8.7	11.6

Group.	910–901 B. C.	920–11	930–21	940–31	950–41	960–51	970–61	980–71	990–81	1000–991	1010–1001	1020–11	1030–21	1040–31	1050–41	1060–51	1070–61	1080–71	1090–81	1100–1091
27. Total growth	8.0	12.0	13.0	16.0	25.0	30.0														
No. of measurements	2	...	...	...	...	2														
Corrected growth	2.8	4.1	4.4	5.2	7.8	9.0														
28 Total growth	29.0	17.0	18.0	20.0	14.0	13.0	22.0	18.0	13.0	17.0	20.0	20.0	22.0	14.0	19.0	19.0	7.0			
& No. of measurements	1															1	1			
29 Corrected growth	13.4	7.8	8.2	8.9	8.1	5.6	9.4	7.6	7.5	7.1	8.2	8.2	8.9	5.6	7.5	7.4	6.6			
30. Total growth	29.0	22.0	26.0	27.0	41.0	37.0	25.0	18.0	11.5	9.5	10.5	11.5	12.0	15.0	11.5	12.5	11.5	8.5	7.0	26.0
No. of measurements	1																			1
Corrected growth	13.5	10.1	11.8	12.3	18.2	16.2	10.8	7.7	4.9	4.0	4.4	4.7	4.9	6.1	4.6	4.9	4.5	3.3	2.7	9.8
31. Total growth	20.0	22.5	24.5	22.5	23.5	27.5	24.0	27.0	27.5	28.0	29.5	26.0	31.5	37.0	32.0	38.0	34.0	36.0	39.0	45.0
No. of measurements	2																			2
Corrected growth	10.6	11.8	12.7	11.5	12.0	13.8	12.0	13.4	13.5	13.5	14.0	12.3	16.3	17.0	14.6	17.2	15.1	15.8	16.9	19.3

Group.	1110–1101 B.C.	1120–11	1130–21	1140–31	1150–41	1160–51	1170–61	1180–71	1190–81	1200–1191	1210–1201	1220–11	1230–21	1240–31	1250–41	1260–51	1270–61	1280–71	1290–81	1300–1291	1310–1301
30 Total growth	23.0																				
No. of measurements	1																				
Corrected growth	8.6																				
31. Total growth	48.0	33.0	50.0	48.0	54.5	73.0	56.5	60.5	59.5	67.0	32.0	8.5	8.0	12.5	11.0	16.5	18.5	21.5	24.5	32.0	42.0
No. of measurements	2																				2
Corrected growth	20.3	13.8	20.8	19.7	22.2	23.5	20.1	23.9	23.3	26.0	12.2	3.2	3.0	4.6	4.0	5.9	6.5	7.3	8.1	10.4	13.1

The first line in each group in Table F indicates the sum of all the measurements of growth included in the group. The second line indicates the number of measurements. The third line indicates the total growth corrected for age and longevity according to Table E. The average growth, corrected or uncorrected, is obtained by dividing the figures in the first or third lines, respectively, by those in the second line.

TABLE G.—*Summary of Growth of Sequoia washingtoniana. Trees measured in 1911 and 1912. By Groups, corrected and uncorrected, including Caspian Factor.*

When the number of measurements is not indicated in column C, it is the same as the figures next above or below.

(A) Date of decade.	(B) Total uncorrected growth.	(C) No. of measurements.	(D) Average uncorrected growth. See fig. 38.	(E) Total corrected growth.	(F) Average corrected growth. See fig. 38.	(G) Caspian factor.	(H) Final corrected average per Caspian. See figs. 50 and 72.	(I) * Mean of three decades.
1901–1910	573.5	44	(13.01)	(351.5)	(7.99)	90.0	(7.11)	—
1891–1900	5404.5	531	(10.18)	(4358.4)	(8.21)	90.1	(7.40)	—
1881–1890	7522.5	748	10.06	5820.5	7.77	90.2	7.00	—
1871–1880	7760.0	782	9.91	5850.6	7.49	90.3	6.75	—
1861–1870	7522.0	784	9.60	5737.4	7.30	90.4	6.60	—
1851–1860	7624.0	785	9.70	5765.2	7.35	90.5	6.65	—
1841–1850	7455.5	....	9.50	5670.0	7.21	90.6	6.53	—
1831–1840	7529.0	....	9.58	5689.0	7.24	90.7	6.56	—
1821–1830	7393.5	....	9.41	5683.5	7.23	90.8	6.56	—
1811–1820	7687.5	....	9.78	5783.6	7.36	90.9	6.68	—
1801–1810	7745.5	....	9.86	5903.7	7.51	91.0	6.83	—
1791–1800	7716.0	....	9.83	5714.3	7.27	91.1	6.62	—
1781–1790	7550.5	....	9.62	5541.2	7.05	91.2	6.42	—
	7755.0							
1771–1780	7661.5	....	9.88	5689.7	7.24	91.3	6.60	—
1761–1770	7891.5	....	9.76	5562.4	7.08	91.4	6.47	—
1751–1760	8099.5	....	10.03	5802.0	7.38	91.5	6.75	—
1741–1750	8112.5	....	10.30	5905.5	7.61	91.6	6.88	—
1731–1740	8079.5	....	10.32	5787.5	7.36	91.7	6.75	—
1721–1730	7992.5	....	10.29	5662.7	7.20	91.8	6.61	—
1711–1720	7913.0	....	10.18	5634.2	7.17	91.9	6.58	—
1701–1710	7913.0	....	10.08	5560.1	7.07	92.0	6.61	—
1691–1700	8198.5	....	10.42	5762.5	7.32	92.1	6.73	—
1681–1690	8342.0	785	10.64	5940.8	7.55	92.2	6.96	—
1671–1680	8358.0	784	10.67	5797.5	7.39	92.3	6.82	—
1661–1670	8256.0	783	10.55	5750.0	7.35	92.4	6.78	—
1651–1660	8210.0	783	10.49	5686.2	7.26	92.5	6.71	—
1641–1650	8303.5	782	10.62	5706.5	7.30	92.6	6.75	—
1631–1640	8227.0	778	10.56	5671.6	7.28	92.7	6.74	—
1621–1630	8360.5	....	10.73	5713.0	7.34	92.8	6.81	—
1611–1620	8448.0	....	10.84	5730.7	7.36	92.9	6.83	—
1601–1610	8321.0	778	10.69	5700.4	7.33	93.0	6.81	—
1591–1600	8171.0	777	10.52	5526.4	7.11	93.1	6.62	—
1581–1590	8260.0	777	10.62	5558.9	7.16	93.2	6.67	—
1571–1580	8335.0	775	10.78	5573.8	7.19	93.3	6.70	—
1561–1570	8551.5	775	11.03	5640.5	7.28	93.4	6.80	—
1551–1560	8402.5	774	10.86	5604.6	7.24	93.5	6.77	—
1541–1550	8371.5	773	10.82	5472.9	7.08	93.6	6.62	—
1531–1540	8422.5	773	10.90	5448.5	7.04	93.7	6.59	—
1521–1530	8371.5	772	10.86	5372.4	6.95	93.8	6.52	—
1511–1520	8405.0	772	10.90	5356.3	6.93	93.9	6.51	—
1501–1510	8124.0	770	10.55	5114.0	6.65	94.0	6.25	—
1491–1500	7853.5	766	10.27	5019.6	6.55	94.1	6.17	—
1481–1490	7840.0	765	10.23	4944.3	6.46	94.2	6.08	—
1471–1480	7749.5	763	10.14	4888.2	6.41	94.3	6.04	—
1461–1470	7877.0	759	10.38	4921.6	6.47	94.4	6.10	—
1451–1460	8203.5	....	10.81	5258.3	6.93	94.5	6.55	—
1441–1450	8556.0	....	11.28	5235.2	6.89	94.6	6.51	—
1431–1440	8709.5	....	11.49	5260.2	6.92	94.7	6.54	—
1421–1430	8831.5	759	11.67	5252.7	6.92	94.8	6.55	—
1411–1420	9047.5	757	11.98	5326.2	7.04	94.9	6.68	—
1401–1410	9070.0	755	12.02	5312.0	7.04	95.0	6.69	—
1391–1400	9206.0	....	12.20	5324.6	7.05	95.1	6.70	—
1381–1390	9545.0	755	12.62	5478.1	7.25	95.2	6.89	—
1371–1380	9936.0	752	13.20	5570.9	7.41	95.3	7.06	—
1361–1370	9946.5	752	13.22	5538.7	7.27	95.4	6.93	—
1351–1360	9900.5	742	13.35	5529.1	7.45	95.5	7.12	—
1341–1350	10121.0	736	13.76	5646.5	7.66	95.6	7.32	—
1331–1340	9975.0	726	13.73	5631.9	7.75	95.7	7.41	—
1321–1330	8796.0	704	12.50	5201.8	7.39	95.8	7.08	—
1311–1320	8354.0	697	12.00	5034.6	7.23	95.9	6.93	—
1301–1310	7687.5	695	11.05	4630.2	6.67	96.0	6.40	—
1291–1300	7359.5	690	10.68	4535.8	6.57	96.1	6.31	—
1281–1290	7274.5	690	10.55	4402.0	6.51	96.2	6.26	—
1271–1280	7257.0	687	10.58	4480.9	6.53	96.3	6.29	—
1261–1270	7366.0	685	10.76	4526.3	6.60	96.4	6.36	—
1251–1260	7383.0	685	10.78	4519.4	6.59	96.5	6.36	—
1241–1250	7406.0	682	10.86	4509.2	6.61	96.6	6.38	—
1231–1240	7417.0	682	10.87	4481.8	6.57	96.7	6.35	—
1221–1230	7787.5	680	11.45	4619.6	6.80	96.8	6.58	—
1211–1220	7598.5	676	11.24	4497.5	6.65	96.9	6.44	—
1201–1210	7495.5	672	11.16	4487.5	6.68	97.0	6.47	—
1191–1200	7793.0	672	11.16	4450.2	6.63	97.1	6.43	—
1181–1190	7287.0	670	10.89	4296.3	6.41	97.2	6.22	—
1171–1180	7455.0	669	11.16	4341.8	6.48	97.3	6.30	—
1161–1170	7376.5	669	11.02	4249.2	6.35	97.4	6.18	—
1151–1160	7347.0	667	11.02	4214.8	6.32	97.5	6.16	—
1141–1150	7555.5	667	11.32	4276.8	6.42	97.6	6.27	—
1131–1140	7866.0	665	11.82	4397.5	6.61	97.7	6.45	—
1121–1130	7937.5	662	12.00	4432.0	6.69	97.8	6.54	—
1111–1120	7985.0	659	12.12	4420.1	6.70	97.9	6.55	—
1101–1110	7975.0	....	12.10	4386.5	6.65	98.0	6.51	—

(A) Date of decade.	(B) Total uncorrected growth.	(C) No. of measurements.	(D) Average uncorrected growth.	(E) Total corrected growth.	(F) Average corrected growth.	(G) Caspian factor.	(H) Final corrected average per Caspian.	(I) * Mean of three decades.
1091–1100	8124.5	659	12.33	4416.5	6.70	98.1	6.57	—
1081–1090	8268.5	659	12.58	4524.5	6.86	98 2	6.74	—
1071–1080	8228.5	659	12.50	4521.0	6.85	98.3	6.74	—
1061–1070	8106.5	658	12.31	4326.9	6.57	98.4	6 46	—
1051–1060	8265.5	655	12.62	4389.2	6.70	98.5	6.60	—
1041–1050	8567.0	655	13.08	4526.1	6.91	98.6	6.82	—
1031–1040	8723.5	653	13.37	4599.5	7.05	98.7	6.96	—
1021–1030	9188.5	651	14.10	4796.7	7.37	98.8	7.28	—
1011–1020	9384.0	649	14.47	4817.6	7.42	98.9	7.34	—
1001–1010	9607.0	647	14.87	4863.5	7.52	99.0	7.45	—
991–1000	9079.0	644	14.10	4578.8	7.11	99.1	7.05	—
981–990	8638.5	644	13.40	4356.6	6.77	99.2	6.71	—
971–980	8488.0	644	13.17	4262.9	6.62	99.3	6.67	—
961–970	8333.0	640	13.02	4174.6	6.52	99.4	6.48	—
951–960	8471.5	640	13.22	4187.6	6.54	99.5	6.50	—
941–950	8406 0	637	13.20	4121.8	6 46	99.6	6.43	—
931–940	8568.5	633	13.53	4180.5	6.60	99.7	6.58	—
921–930	8765.5	630	13.90	4258.3	6.76	99.8	6.75	—
911–920	8795.0	624	14.08	4271.9	6.83	99.9	6.82	—
901–910	8803.0	620	14.21	4254.8	6.86	100.0	6.86	—
891–900	8727.5	612	14.27	4172.4	6.82	100.0	6.82	—
881–890	8367.5	607	13.80	4002.2	6.60	100.0	6.60	—
871–880	8112.5	605	13.41	3774.7	6.24	100.0	6.24	—
861–870	8120.5	599	13.53	3847.9	6.42	100.0	6.42	—
851–860	8150.0	595	13.70	3740.4	6.28	100.0	6.28	—
841–850	8220.5	595	13.80	3820.8	6.42	100.0	6.42	—
831–840	8175.5	590	13.85	3807.7	6.45	100.0	6.45	—
821–830	8060.0	589	13.70	3734.4	6.34	100.0	6.34	—
811–820	8210.0	586	14.03	3751.5	6.40	100.0	6.40	—
801–810	7963.0	578	13.77	3687.3	6.38	100.0	6.38	—
791–800	8171.0	576	14.20	3741.6	6.50	100.0	6.50	—
781–790	8136.5	576	14.11	3673.7	6.38	100.0	6.38	—
771–780	7750.0	558	13.90	3530.5	6.32	100.0	6.32	—
761–770	7271.0	558	13.04	3383.7	6.06	100.0	6.06	—
751–760	7605.5	556	13.70	3500.6	6.31	100.0	6.31	—
741–750	7780.0	552	14.11	3458.0	6.26	100.0	6.26	—
731–740	7778.0	552	14.11	3400.4	6.17	100.0	6.17	—
721–730	7442.5	545	13.63	3330.3	6.11	100.0	6.11	—
711–720	7781.5	543	14.32	3307.8	6.08	100.0	6.08	—
701–710	7625.0	537	14.21	3361.9	6.26	100.0	6.26	—
691–700	7526.0	527	14.30	3319.5	6.30	10.00	6.30	—
681–690	7349.0	518	14.18	3269.9	6.30	100.0	6.30	—
671–680	7290.5	517	14.10	3237.7	6.25	100.0	6.25	—
661–670	7156.0	511	14.01	3154.0	6.17	100.0	6.17	—
651–660	7074.5	504	14.03	3101.2	6.15	100.0	6.15	—
641–650	6918.5	499	13.88	3029.1	6.07	100.0	6.07	—
631–640	6943.0	489	14.18	3057.8	6.24	100.0	6.24	—
621–630	6852.0	483	14.18	3008.6	6.22	100.0	6.22	—
611–620	7179.0	471	15 28	3114.7	6.60	100.0	6.60	—
601–610	6999.0	460	15.20	3138.3	6.81	100.0	6.81	—
591–600	6698.0	451	14.85	3041.6	6.75	100.0	6.75	—
581–590	6493 0	442	14.70	2932.2	6.64	100.0	6.64	—
571–580	6517.0	435	15.00	2883.1	6.63	100.0	6.63	—
561–570	6282.5	429	14.65	2785.2	6.48	100.0	6.48	—
551–560	5999.5	425	14.12	2676.0	6.29	100.0	6.29	—
541–550	6245.5	422	14.81	2773.7	6.58	100.0	6.58	—
531–540	5762.0	411	14.02	2623.6	6.38	100.0	6.38	—
521–530	5794.0	409	14.17	2642.2	6.46	100.0	6.46	—
511–520	5773.5	404	14.30	2603.8	6.44	100.0	6.44	—
501–510	5700.5	402	14.22	2593.6	6.45	100.0	6.45	—
491–500	5644.0	397	14.22	2526.9	6.36	100.0	6.36	—
481–490	5712.0	395	14.46	2524.9	6.38	100.0	6.38	—
471–480	5782.0	395	14.65	2543.6	6.44	100.0	6.44	—
461–470	5620.5	393	14.30	2477.0	6.30	100.0	6.30	—
451–460	5552.5	387	14.35	2433.5	6.28	100.0	6.28	—
441–450	5488.0	381	14.40	2395.4	6 29	100.0	6.29	—
431–440	5192.5	367	14.13	2317.5	6.31	100.0	6.31	—
421–430	5292.5	362	14.61	2344.1	6.48	100.0	6.48	—
411–420	4819.0	350	13.73	2201.7	6.29	100.0	6.29	—
401–410	4937.0	350	14.11	2236.0	6.38	100.0	6.38	—
391–400	4922.4	348	14.15	2313.3	6.65	100.2	6.66	—
381–390	4959.5	344	14.42	2234.5	6.48	100.4	6.50	—
371–380	5005.0	336	14.90	2262.5	6 74	100.6	6.78	—
361–370	4907.5	326	15.07	2187.9	6.71	100.8	6.76	—
351–360	4847.5	321	15.10	2164.9	6 75	101.0	6 82	—
341–350	4772.5	317	15.05	2111.9	6.65	101.2	6.73	—
331–340	4746.5	311	15.25	2108.5	6.77	101.4	6.87	—
321–330	4785.0	309	15.50	2082.0	6.74	101.6	6.83	—
311–320	4570.0	306	14.92	2089.0	6.82	101.8	6.95	—
301–310	4546.0	295	15.40	2015.4	6.82	102.0	6.96	—
291–300	4577.0	294	15.58	1992.2	6.78	102.2	6.94	—

TABLE G.—*Summary of Growth of Sequoia washingtoniana. Trees measured in 1911 and 1912. By Groups, corrected and uncorrected, including Caspian Factor—Continued.*

When the number of measurements is not indicated in column C, it is the same as the figures next above or below.

(A) Date of decade.	(B) Total uncorrected growth.	(C) No. of measurements.	(D) Average uncorrected growth.	(E) Total corrected growth.	(F) Average corrected growth.	(G) Caspian factor.	(H) Final corrected average per Caspian.	(I) * Mean of three decades.
281-290	4527.0	292	15.50	1975.1	6.76	102.4	6.92	—
271-280	4591.0	286	16.05	1975.3	6 90	102.6	7.08	—
261-270	4675.0	284	16.47	1998.4	7 03	102.8	7.23	—
251-260	4571.0	283	16.15	1960.6	6.93	103.0	7.14	—
241-250	4601.5	280	16.42	1956.1	6.97	103.2	7.19	—
231-240	4479.0	272	16.50	1913.4	7.04	103.4	7.28	—
221-230	4497.0	265	16.98	1915.5	7.22	103.6	7.49	—
211-220	4416.0	260	17.00	1863.4	7.16	103.8	7.43	—
201-210	4263.7	253	16.85	1805.4	7.13	104.0	7.42	—
191-200	4112.5	247	16.67	1759.1	7.12	104.2	7.42	—
181-190	3771.0	239	15.78	1615.8	6.75	104.4	7.05	—
171-180	3680.0	237	15.53	1579.4	6.66	104.6	6.97	—
161-170	3722.5	235	15.86	1586.1	6.75	104.8	7.08	—
151-160	3682.0	232	15.88	1570.9	6.77	105.0	7.11	—
141-150	3750.5	230	16.60	1569.2	6.81	105.2	7.16	—
131-140	3608.5	225	16 05	1522.1	6.76	105.4	7.12	—
121-130	3624.5	222	16.32	1518.7	6.84	105.6	7.27	—
111-120	3563.0	220	16.40	1479.4	6.72	105.8	7.11	—
101-110	3439.5	215	16.00	1445.5	6.72	106.0	7.12	—
91-100	3282.0	209	15.72	1384.4	6.63	106.2	7.04	—
81-90	3296.0	207	15.90	1383.9	6.68	106.4	7.11	—
71-80	3611.5	207	17.50	1491 2	7.21	106.6	7.68	—
61-70	3558.5	203	17.51	1456.4	7.17	106.8	7.66	—
51-60	3432.5	198	17.32	1420.8	7.18	107.0	7.69	—
41-50	3480.0	196	17.77	1422.2	7.21	107.2	7.73	—
31-40	3214.0	184	17.50	1330.1	7.24	107.4	7.77	—
21-30	3120.0	180	17.35	1284.0	7.14	107.6	7.69	—
11-20	3117.0	177	17.65	1279.3	7.22	107.8	7.78	—
1-10 A. D.	2968.5	173	17.17	1219.0	7.05	108.0	7.61	—
10-1 B. C.	2927.0	173	16.84	1188.1	6.86	108.2	7.43	—
20-11	2918.0	167	17.43	1190.7	7.14	108.4	7.73	—
30-21	2682.5	157	17.10	1117.0	7.10	108.6	7.71	—
40-31	2590.5	154	16.82	1076.0	6.98	108.8	7.59	—
50-41	2552.5	150	17.01	1061.0	7.08	109.0	7.72	—
60-51	2464.0	150	16.42	1013.8	6.77	109.2	7.40	—
70-61	2466.5	150	16.42	1004.2	6.70	109.4	7.33	—
80-71	2479.5	148	16.75	1002.2	6.77	109.6	7.42	—
90-81	2418.0	145	16.68	982.9	6.78	109.8	7.44	—
100-91	2360.5	143	16.50	960.5	6.72	110.0	7.39	—
110-101	2337.0	141	16.59	935.7	6.64	110.2	7.32	—
120-111	2234.5	140	15.95	868.2	6.20	110.4	6.85	—
130-121	2172.5	139	15.63	873.4	6.28	110.6	6.95	—
140-131	2081.0	137	15.20	830.1	6 07	110.8	6.73	—
150-141	2057.0	135	15.22	818.6	6.06	111.0	6.73	—
160-151	1996.5	133	15.00	792.6	5.96	111.2	6.63	—
170-161	2004.0	131	15.30	789.9	6.02	111.4	6.70	—
180-171	2005.0	130	15.42	780.1	6.00	111.6	6.70	—
190-181	1896.0	125	15.18	739.0	5.91	111.8	6 60	—
200-191	1749.5	118	14.80	692.0	5.87	112.0	6.57	—
210-201	1850.0	118	15.69	717.5	6.08	112.2	6.83	—
220-211	1612.5	112	14.40	640.1	5.72	112.4	6.43	—
230-221	1632.5	105	15.52	645.3	6.15	112.6	6.93	—
240-231	1680.5	103	16.30	651.7	6.33	112.8	7.14	*
250-241	1768.0	97	18.22	681.8	7.02	113.0	7.94	7.78
260-251	1681.0	89	18.90	651.9	7.31	113.2	8.27	8 17
270-261	1575.5	84	18.75	614.5	7.31	113.4	8.29	8.45
280-271	1356.0	71	19.10	549.0	7.73	113.6	8.78	8.66
290-281	1299.5	68	19.10	531.8	7.82	113.8	8.90	8.75
300-291	1144 0	64	17.88	481.4	7.52	114.0	8.57	8.58
310-301	1117.5	64	17.45	464.5	7.25	114.2	8.28	8.32
320-311	1086.5	63	17.23	446.9	7.09	114.4	8.10	8.21
330-321	1111.0	63	17.61	453.3	7.20	114.6	8.25	8.34
340-331	1086.0	59	18.40	446.0	7.56	114.8	8.68	8.45
350-341	1054.5	59	17.89	431.7	7.32	115.0	8.41	8.63
360-351	1084.0	57	19.02	436.4	7.66	115.0	8.81	8.67
370-361	1110.0	57	19.48	436.3	7.65	115.0	8.80	9.02
380-371	1077.0	52	20.66	428.9	8.24	115.0	9.46	9.06
390-381	1008.5	52	19.38	403.0	7.75	115.0	8.91	9.23
400-391	1084.5	52	20.82	422.2	8.11	115.0	9.33	9.23
410-401	1075.0	51	21.08	419.5	8.22	115.0	9.45	9.22
420-411	908.5	47	19.32	363.9	7.73	115.0	8.89	9.12
430-421	840.0	43	19.53	337.1	7.85	115.0	9.03	8.82
440-431	766.5	41	18.70	309.2	7.53	115.0	8.65	8.78
450-441	768.0	41	18.75	309.1	7.53	115.0	8.65	8.44
460-451	718.5	40	17.98	278.8	6.97	115.0	8.01	7.95
470-461	546.5	36	15.18	225.3	6.25	115.0	7 19	7.60
480-471	472.0	30	15.72	200.1	6.70	115.0	7.70	7.39
490-481	348.5	26	13.40	164.7	6.32	115.0	7.27	7.52
500-491	383.5	26	14.74	171.9	6.60	115.0	7.58	7.37
510-501	330.5	24	13 78	151.2	6.30	115.0	7.25	7.24
520-511	338.5	24	14.10	144.0	6.90	115.0	6.90	7.39
530-521	324.0	22	14.72	153.2	6.97	115.0	8.01	7.32
540-531	291.5	22	13.24	134.9	6.13	115.0	7 05	7.61
550-541	316.5	22	14 10	148.3	6.75	115.0	7.76	7.47
560-551	305.0	20	15.25	132.3	6.62	115.0	7.61	7.81
570-561	308.0	20	15.40	142.1	7.11	115.0	8.17	7.81
580-571	287.0	19	15.10	128.3	6.75	115.0	7.76	7.77
590-581	193.5	15	12.90	96.3	6.42	115.0	7.38	7.17
600-591	167.5	....	12.50	83.1	5.54	115.0	6.37	6.92
610-601	192.0	....	12.80	91.4	6.08	115.0	7.00	6.96
620-611	209.0	....	13.95	98.0	6.54	115.0	7.51	7.41
630-621	226.0	15	15.08	102.1	6.71	115.0	7.71	7.73
640-631	186.5	13	14.35	90.5	6.93	115 0	7.96	7.86
650-641	187.5	....	14.42	89.5	6.88	115.0	7.90	7.92
660-651	193.0	....	14.85	89.4	6 88	115.0	7.90	8.29
670-661	223.5	....	17.20	102.4	7.88	115.0	9.06	8.99
680-671	224.0	....	17.24	101.9	7.84	115.0	9.01	8.81
690-681	214.0	....	16.48	94.4	7.26	115.0	8.35	8.30
700-691	192.5	....	14.80	85.3	6.57	115.0	7.55	7.84
710-701	201.0	13	15.45	86.0	6.62	115.0	7.61	7.37
720-711	138.0	11	12 55	66.5	6.05	115.0	6.96	7.40
730-721	154.0	....	14.00	73.1	6.64	115.0	7 64	7.67
740-731	171.5	....	15 60	80.2	7.30	115.0	8.40	7.95
750-741	181 0	....	16.46	84.2	7.65	115.0	7.80	7.83
760-751	156.5	....	14.22	69.6	6.33	115.0	7.28	7.33
770-761	148.0	....	13.46	66.1	6.00	115.0	6.90	6.90
780-771	136.5	....	12.40	62.3	5.67	115.0	6.52	0.84
790-781	154.0	....	14.00	67.8	6 17	115.0	7.10	6.83
800-791	150.0	....	13.63	65.8	5.98	115.0	6.88	6.87
810-801	147.5	....	13.40	63.4	5 76	115.0	6.63	7.02
820-811	175.5	....	15.95	72.2	6.56	115 0	7.55	7.24
830-821	180.0	....	16.38	72.9	6.62	115.0	7.61	7.72
840-831	190.5	11	17.32	76.6	6.96	115.0	8.00	7.72
850-841	142 0	9	15.80	59.2	6.56	115.0	7.55	7.70
860-851	140.0	9	15.56	59.1	6.56	115.0	7.55	7.35
870-861	137.0	9	15.22	54.4	6 04	115.0	6 95	7.31
880-871	84.0	6	14 00	38.9	6.47	115.0	7.41	7.16
890-881	82.0	....	13.68	37.1	6.17	115.0	7.09	7.56
900-891	93.5	....	15.58	43.5	7.08	115 0	8.15	7 65
910-901	86.0	....	14.35	40.3	6 72	115.0	7 72	7.45
920-911	73.5	....	12.26	33.8	5.62	115.0	6.47	7.10
930-921	81.5	....	13.60	37.1	6.17	115.0	7.10	7.94
940-931	85.5	....	14.25	37.9	6.31	115.0	7.26	7.57
950-941	103.5	....	17.22	44.1	7.34	115.0	8.44	8.07
960-951	107.5	6	17.90	44.6	7.42	115.0	8.52	8 74
970-961	71.0	4	17.75	32.2	8.05	115.0	9.25	8.67
980-971	63.0	....	15.75	28.7	7.17	115.0	8.25	8.32
990-981	57.0	....	14.25	25.0	6.48	115.0	7.45	7.59
1000-991	54.5	....	13.62	24.6	6.15	115.0	7.07	7.39
1010-1001	60.0	....	15.00	26.6	6.65	115 0	7.65	7.32
1020-1011	57.5	....	14.37	25.2	6.30	115.0	7.25	7.81
1030-1021	68.5	....	17.12	29.9	7.42	115.0	8.53	8 01
1040-1031	66.0	....	16.50	28.7	7.17	115.0	8 25	8.15
1050-1041	62.5	....	15.62	26.7	6.67	115.0	7.67	8.13
1060-1051	69.5	....	17.37	29.5	7.37	115.0	8.47	7.89
1070-1061	62.5	4	15.62	26.2	6.55	115.0	7.53	7.77
1080-1071	44.5	3	14.85	19.1	6.36	114.0	7.31	7.45
1090-1081	46.0	....	15.33	19.6	6.53	113.0	7.50	8.55
1100-1091	71.0	....	23 67	29.1	9.70	112.0	10.85	9.74
1110-1101	71.0	3	23.67	28.9	9.63	111.0	10.68	9.71
1120-1111	33.0	2	16.50	13.8	6.90	110.0	7.60	9.88
1130-1121	50.0	....	25.00	20.8	10.40	109.0	11.35	9.86
1140-1131	48.0	....	21.00	19.7	9.85	108.0	10.62	11.29
1150-1141	54.0	....	27.25	22.2	11.10	107.0	11.90	12.71
1160-1151	73.0	....	36.50	29.5	14.75	106.0	15.62	12.85
1170-1161	50.5	....	25.25	20.1	10.50	105.0	11.03	13.03
1180-1171	60.5	....	30.25	23.9	11.95	104.0	12.45	11.83
1190-1181	59.5	....	24.75	23.3	11.65	103.0	12.00	12.57
1200-1191	67 0	....	33.50	26.0	13.00	102.0	13.26	10.47
1210-1201	32.0	....	16.00	12.2	6.10	101.0	6.16	7.01
1220-1211	8.5	....	4.25	3.2	1.60	100.0	1.60	3.09
1230-1221	8.0	....	4 00	3.0	1.50	100.0	1.50	1.80
1240-1231	12.5	....	6.25	4.6	2.30	100.0	2.30	1.93
1250-1241	11.0	....	5.50	4.0	2.00	100.0	2.00	2.42
1260-1251	16.5	....	8.25	5.9	2.95	100.0	2.95	2.73
1270-1261	18.5	....	9 25	6.5	3.25	100.0	3.25	3.28
1280-1271	21.5	....	10.75	7.3	3.65	100.0	3.65	3.65
1290-1281	24.5	....	12.25	8.1	4.05	100.0	4.05	4.27
1300-1291	32.0	....	16.00	10.4	5.20	100.0	5.20	5.27
1310-1301	42.0	2	21.00	13.1	6.55	100.0	6.55	......

* At 240 B. C. the number of measurements falls below 100. Previous to this date, in order to avoid violent and sudden fluctuations due to the small number of trees, the mean of 3 decades has been substituted for the values of column H in our final curve of climatic fluctuations, fig. 50.

When the number of trees is not indicated, it is the same as the figure next above or below the blank. In the column showing average growth the figures under A indicate the values where allowance is made for the dropping out of group after group of trees in the earlier centuries, while under B no allowance has been made. Where only one set of figures is given in the column of average growth, the values A and B are the same. In plotting the curves of figure 31 the values under B have in all cases been used. (See figure 31.)

Date.	Sequoia sempervirens.				Red Fir, Tahoe, California.				Red Fir, Idaho.				Douglas Fir, Idaho.			
	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth A.	Average growth B.	30-year mean of A.	No. of trees.	Average growth A.	Average growth B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.
1901-1910	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
1891-1900	227	0.352	—	—	68	0.501	—	—	73	0.402	—	—	29	0.300	—	—
1881-1890	......	0.367	—	0.375	......	0.462	—	0.474	......	0.431	......	0.421	......	0.400	......	0.372
1871-1880	......	0.407	—	0.399	......	0.460	......	0.455	......	0.431	......	0.434	......	0.417	......	0.387
1861-1870	......	0.424	—	0.425	......	0.443	......	0.458	......	0.139	......	0.436	......	0.345	......	0.392
1851-1860	......	0.445	—	0.457	......	0.472	......	0.462	......	0.439	......	0.455	......	0.414	......	0.376
1841-1850	......	0.502	—	0.472	......	0.162	......	0.460	......	0.488	......	0.478	......	0.370	......	0.356
1831-1840	......	0.469	—	0.479	......	0.446	......	0.457	......	0.508	......	0.522	......	0.284	......	0.352
1821-1830	......	0.467	—	0.485	......	0.463	......	0.467	......	0.570	......	0.554	......	0.402	......	0.377
1811-1820	......	0.520	—	0.502	......	0.492	......	0.499	......	0.585	......	0.535	......	0.445	......	0.435
1801-1810	......	0.520	—	0.531	......	0.543	......	0.505	......	0.450	......	0.491	......	0.457	......	0.412
1791-1800	......	0.554	—	0.529	......	0.181	......	0.504	......	0.438	......	0.486	......	0.335	......	0.367
1781-1790	......	0.512	—	0.524	......	0.488	......	0.476	......	0.570	......	0.507	......	0.310	......	0.338
1771-1780	......	0.506	—	0.514	......	0.459	......	0.478	......	0.514	......	0.551	......	0.370	......	0.358
1761-1770	......	0.524	—	0.530	......	0.487	......	0.481	......	0.568	......	0.519	......	0.394	......	0.385
1751-1760	......	0.561	—	0.557	......	0.498	......	0.499	......	0.475	......	0.533	......	0.391	......	0.400
1741-1750	......	0.586	—	0.580	......	0.512	......	0.520	......	0.557	......	0.539	......	0.416	......	0.421
1731-1740	......	0.592	—	0.589	......	0.551	......	0.536	......	0.585	......	0.560	......	0.455	......	0.414
1721-1730	......	0.588	—	0.591	......	0.545	......	0.554	......	0.538	......	0.585	......	0.381	......	0.402
1711-1720	......	0.592	—	0.584	......	0.565	......	0.545	......	0.632	......	0.587	......	0.371	......	0.384
1701-1710	227	0.573	—	0.587	68	0.524	......	0.543	73	0.591	......	0.587	29	0.399	......	0.410
1691-1700	216	0.596	—	0.578	12	0.540	0.542	0.524	61	0.537	0.510	0.548	28	0.461	0.450	0.422
1681-1690	......	0.566	—	0.568	......	0.509	0.557	0.531	46	0.517	0.497	0.566	26	0.405	0.402	0.448
1671-1680	......	0.542	—	0.547	......	0.544	0.603	0.533	34	0.645	0.498	0.617	22	0.478	0.469	(0.438)
1661-1670	......	0.532	—	0.540	......	0.547	0.622	0.534	29	0.690	0.533	(0.695)	(14	0.430	0.413)	......
1651-1660	......	0.535	—	0.537	42	0.510	0.586	0.519	(18	0.750	0.608)	......	......	......	......	......
1641-1650	216	0.543	—	0.538	32	0.501	0.473	0.483	......	......	......	......	......	......	......	......
1631-1640	208	0.536	—	0.532	......	0.438	0.400	0.445	......	......	......	......	......	......	......	......
1621-1630	......	0.517	—	0.520	......	0.397	0.360	0.419	......	......	......	......	......	......	......	......
1611-1620	......	0.506	—	0.516	32	0.421	0.377	0.429	......	......	......	......	......	......	......	......
1601-1610	208	0.525	—	0.525	22	0.470	0.430	0.476	......	......	......	......	......	......	......	......
1591-1600	201	0.544	—	0.538	......	0.537	0.377	0.553	......	......	......	......	......	......	......	......
1581-1590	......	0.545	—	0.541	......	0.652	0.544	0.594	......	......	......	......	......	......	......	......
1571-1580	......	0.534	—	0.537	......	0.592	0.473	0.621	......	......	......	......	......	......	......	......
1561-1570	......	0.533	—	0.532	......	0.633	0.507	0.629	......	......	......	......	......	......	......	......
1551-1560	......	0.529	—	0.531	......	0.663	0.532	0.650	......	......	......	......	......	......	......	......
1541-1550	201	0.530	—	0.529	22	0.655	0.524	(0.613)	......	......	......	......	......	......	......	......
1531-1540	182	0.529	—	0.536	(12	0.520	0.482)	......	......	......	......	......	......	......	......	......
1521-1530	......	0.549	—	0.538	......	......	......	......	......	......	......	......	......	......	......	......
1511-1520	182	0.537	—	0.543	......	......	......	......	......	......	......	......	......	......	......	......
1501-1510	146	0.542	—	0.550	......	......	......	......	......	......	......	......	......	......	......	......
1491-1500	......	0.572	—	0.562	......	......	......	......	......	......	......	......	......	......	......	......
1481-1490	......	0.571	—	0.572	......	......	......	......	......	......	......	......	......	......	......	......
1471-1480	......	0.573	—	0.574	......	......	......	......	......	......	......	......	......	......	......	......
1461-1470	......	0.577	—	0.584	......	......	......	......	......	......	......	......	......	......	......	......
1451-1460	146	0.602	—	0.604	......	......	......	......	......	......	......	......	......	......	......	......
1441-1450	112	0.633	—	0.619	......	......	......	......	......	......	......	......	......	......	......	......
1431-1440	......	0.622	—	0.628	......	......	......	......	......	......	......	......	......	......	......	......
1421-1430	......	0.624	—	0.617	......	......	......	......	......	......	......	......	......	......	......	......
1411-1420	......	0.606	—	0.602	......	......	......	......	......	......	......	......	......	......	......	......
1401-1410	112	0.576	—	0.587	......	......	......	......	......	......	......	......	......	......	......	......
1391-1400	99	0.578	—	0.572	......	......	......	......	......	......	......	......	......	......	......	......
1381-1390	......	0.563	—	0.572	......	......	......	......	......	......	......	......	......	......	......	......
1371-1380	......	0.580	—	0.583	......	......	......	......	......	......	......	......	......	......	......	......
1361-1370	99	0.606	—	0.576	......	......	......	......	......	......	......	......	......	......	......	......
1351-1360	83	0.547	—	0.583	......	......	......	......	......	......	......	......	......	......	......	......
1341-1350	......	0.596	—	0.582	......	......	......	......	......	......	......	......	......	......	......	......
1331-1340	......	0.602	—	0.598	......	......	......	......	......	......	......	......	......	......	......	......
1321-1330	83	0.596	—	......	......	......	......	......	......	......	......	......	......	......	......	......

Date.	Jeffrey Pine, S. California.				Sugar Pine, S. Calif.				Bull Pine, S. Calif.				Shortleaf Pine, Arkansas.			
	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.
1901-1910	177	0.508	—	—	—	—		—	—	—		—				
1891-1900		0.722	—	0.620	31	0.71		—	32	0.584		—	245	0.393		—
1881-1890		0.630	—	0.658		0.81		0.77		0.610		0.612		0.353		0.382
1871-1880		0.621	—	0.603		0.78		0.82		0.641		0.622		0.401		0.369
1861-1870		0.558	—	0.587		0.86		0.81		0.615		0.614		0.352		0.384
1851-1860		0.581	—	0.557		0.79		0.83		0.585		0.595		0.399		0.382
1841-1850		0.532		0.563		0.83		0.85		0.585		0.586		0.394		0.372
1831-1840		0.577		0.558		0.94		0.85		0.588		0.599		0.323		0.349
1821-1830		0.564		0.571		0.77		0.86		0.625		0.609		0.331		0.361
1811-1820		0.572		0.602		0.88		0.86		0.613		0.603		0.428		0.388
1801-1810		0.661		0.630		0.94		0.86		0.570		0.584		0.405		0.407
1791-1800		0.657		0.644		0.77		0.83		0.570		0.571		0.388		0.399
1781-1790		0.614		0.631		0.78		0.81		0.573		0.579		0.403		0.406
1771-1780		0.623		0.612		0.87		0.83		0.594		0.573		0.427		0.413
1761-1770		0.600		0.610		0.83		0.80		0.551		0.564		0.409		0.421
1751-1760		0.606		0.631		0.70		0.77		0.546		0.544		0.428		0.431
1741-1750		0.687		0.648		0.78		0.75		0.535		0.539		0.456		0.428
1731-1740		0.652		0.667		0.77		0.78		0.536		0.560		0.399		0.406
1721-1730		0.663		0.633		0.79		0.80		0.611		0.574		0.363		0.379
1711-1720	177	0.584		0.630		0.85		0.85		0.576		0.586		0.376		0.372
1701-1710	68	0.643	0.651	0.618		0.90		0.88		0.570		0.568	245	0.377		0.372
1691-1700		0.627	0.668	0.630		0.87		0.90	32	0.558		0.560	170	0.363	0.366	0.370
1681-1690		0.621	0.659	0.600		0.94		0.94	21	0.551	0.553	0.546	95	0.369	0.391	0.348
1671-1680		0.553	0.606	0.572		1.00		0.95		0.528	0.530	0.549	31	0.313	0.366	(0.324)
1661-1670	68	0.541	0.595	0.569		0.92		0.96		0.569	0.571	0.542	(16	0.289	0.316)	
1651-1660	26	0.603	0.632	0.585		0.97		0.95	21	0.528	0.530	(0.546)				
1641-1650		0.612	0.626	0.612		0.97		0.92	(11	0.541	0.635)					
1631-1640		0.620	0.636	0.613		0.81		0.87								
1621-1630		0.608	0.609	0.620	31	0.84										
1611-1620	26	0.633	0.685	(0.627)												
1601-1610	(10	0.640	0.688)													
1591-1600																
1581-1590																
1571-1580																
1561-1570																
1551-1560																
1541-1550																
1531-1540																
1521-1530																
1511-1520																
1501-1510																

Date.	White Oak, Missouri.				White Oak, West Virginia.				Tulip Poplar, West Virginia.				Beech, Lewis Co., New York.			
	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B.	30-year mean of A.	No. of trees.	Average growth. A.	Average growth. B	30-year mean of A.
1901-1910	—	—		—	—	—		—	—	—		—	—	—		—
1891-1900	26	0.621		—	728	0.63		—	107	0.334		—	46	0.505		—
1881-1890		0.674		0.633		0.68		0.65		0.365		0.352		0.577		0.576
1871-1880		0.604		0.637		0.63		0.66		0.358		0.345		0.647		0.583
1861-1870		0.632		0.620		0.66		0.62		0.313		0.331		0.525		0.558
1851-1860		0.625		0.645		0.58		0.61		0.322		0.332		0.502		0.514
1841-1850		0.678		0.670		0.60		0.58		0.331		0.331		0.515		0.515
1831-1840		0.706		0.677		0.56		0.58		0.341		0.332		0.529		0.534
1821-1830		0.648		0.635		0.59		0.58		0.323		0.329		0.558		0.559
1811-1820		0.551		0.602		0.59		0.60		0.324		0.331		0.589		0.577
1801-1810		0.606		0.604		0.61		0.62		0.349		0.340		0.583		0.577
1791-1800		0.653		0.653		0.67		0.66		0.348		0.350		0.559		0.548
1781-1890		0.698		0.703		0.71		0.70		0.352		0.343		0.503		0.513
1771-1780		0.756		0.693		0.71		0.68		0.330		0.336		0.478		0.493
1761-1770		0.625		0.665		0.62		0.63		0.327		0.327		0.499		0.486
1751-1760		0.613		0.637		0.55		0.58		0.324		0.326		0.481		0.485
1741-1750		0.673		0.675		0.56		0.57		0.327		0.330		0.475		0.486
1731-1740		0.740		0.750		0.59		0.58		0.339		0.337		0.501		0.496
1721-1730		0.837		0.788		0.59		0.60		0.344		0.340		0.512		0.523
1711-1720		0.788		0.796		0.63		0.611		0.338		0.344		0.557		0.535
1701-1710	26	0.762		0.754	728	0.613		0.621	107	0.349		0.349	46	0.536		0.529
1691-1700	25	0.713	0.691	0.694	620	0.620	0.64	0.629	91	0.361	0.355	0.347	36	0.484	0.478	0.513
1681-1690	25	0.607	0.575	0.657	446	0.593	0.62	0.608	76	0.332	0.320	0.347	26	0.520	0.511	0.491
1671-1680	23	0.652	0.560	(0.628)	252	0.612	0.63	0.605	62	0.347	0.343	0.342	20	0.469	0.491	(0.493)
1661-1670	(17	0.625	0.553)		134	0.611	0.62	0.613	51	0.346	0.336	0.342	(13	0.485	0.417)	
1651-1660					82	0.615	0.63	0.618	38	0.332	0.314	0.335				
1641-1650					60	0.629	0.58	0.630	30	0.328	0.305	0.350				
1631-1640					54	0.647	0.58	0.651	21	0.389	0.350	(0.379)				
1621-1630					44	0.676	0.58	0.680	(13	0.420	0.345)					
1611-1620					31	0.707	0.54	(0.720)								
1601-1610					(18	0.778	0.56)									

Date.	Yellow Pine, Idaho. No. of trees.	Yellow Pine, Idaho. Average growth. A.	Yellow Pine, Idaho. Average growth. B.	Yellow Pine, Idaho. 30-year mean of A.	Yellow Pine, New Mexico. No. of trees.	Yellow Pine, New Mexico. Average growth. A.	Yellow Pine, New Mexico. Average growth. B.	Yellow Pine, New Mexico. 30-year mean of A.	Spruce, West Virginia. No. of trees.	Spruce, West Virginia. Average growth. A.	Spruce, West Virginia. Average growth. B.	Spruce, West Virginia. 30-year mean of A.	Red Spruce, Maine. No. of trees.	Red Spruce, Maine. Average growth. A.	Red Spruce, Maine. Average growth. B.	Red Spruce, Maine. 30-year mean of A.
1901-1910	217	0.204		—	272	0.260		—	—	—		—	—	—		—
1891-1900		0.205		0.202		0.236		0.238	223	0.380		—	163	0.255		—
1881-1890		0.198		0.203		0.217		0.227		0.287		0.327		0.235		0.229
1871-1880		0.207		0.196		0.227		0.226		0.313		0.327		0.197		0.217
1861-1870		0.182		0.190		0.234		0.234		0.380		0.337		0.218		0.224
1851-1860		0.182		0.177		0.241		0.239		0.317		0.340		0.257		0.243
1841-1850		0.166		0.191		0.213		0.240		0.324		0.321		0.265		0.263
1831-1840		0.203		0.196		0.235		0.234		0.322		0.322		0.267		0.270
1821-1830		0.215		0.206		0.223		0.231		0.320		0.322		0.277		0.257
1811-1820		0.204		0.201		0.236		0.236		0.324		0.317		0.226		0.241
1801-1810		0.184		0.181		0.250		0.247		0.310		0.300		0.181		0.192
1791-1800		0.154		0.168		0.255		0.251		0.269		0.278		0.170		0.181
1781-1790		0.166		0.168		0.250		0.251		0.264		0.277		0.193		0.182
1771-1780		0.185		0.172		0.250		0.251		0.309		0.294		0.183		0.186
1761-1770		0.164		0.172		0.253		0.250		0.319		0.311		0.183		0.193
1751-1760		0.167		0.168		0.248		0.256		0.304		0.307		0.213		0.198
1741-1750		0.173		0.172		0.250		0.251		0.290		0.298		0.198		0.200
1731-1740		0.177		0.173		0.254		0.252		0.290		0.293		0.190		0.195
1721-1730		0.169		0.170		0.252		0.253		0.291		0.296		0.196		0.196
1711-1720	217	0.164		0.168		0.254		0.252		0.306		0.300		0.201		0.215
1701-1710	213	0.172	0.174	0.169	272	0.251		0.251	223	0.302		0.306	163	0.249		0.238
1691-1700	205	0.171	0.174	0.170	246	0.247	0.246	0.248	204	0.309	0.305	0.327	151	0.265	0.269	0.268
1681-1690	187	0.168	0.173	0.163	208	0.246	0.245	0.249	179	0.340	0.334	0.326	142	0.290	0.303	0.279
1671-1680	169	0.164	0.172	0.159	178	0.255	0.252	0.259	147	0.328	0.305	0.330	129	0.281	0.294	0.265
1661-1670	156	0.144	0.155	0.151	149	0.276	0.268	0.272	126	0.321	0.283	0.319	110	0.223	0.239	0.228
1651-1660	150	0.144	0.154	0.147	113	0.286	0.277	0.289	102	0.308	0.235	0.318	93	0.180	0.185	0.203
1641-1650	136	0.153	0.162	0.145	87	0.295	0.281	0.239	85	0.324	0.228	0.331	73	0.206	0.213	0.189
1631-1640	106	0.137	0.145	0.154	67	0.285	0.276	0.282	66	0.368	0.238	0.370	58	0.182	0.162	0.195
1621-1630	67	0.171	0.193	0.155	50	0.267	0.267	0.272	60	0.117	0.273	0.398	47	0.196	0.159	0.188
1611-1620	56	0.156	0.185	0.158	34	0.266	0.275	0.272	45	0.410	0.255	0.117	38	0.185	0.149	0.202
1601-1610	51	0.147	0.183	0.147	(18	0.285	—)		37	0.423	0.271	0.433	33	0.226	0.167	0.219
1591-1600	49	0.137	0.176	0.142					27	0.465	0.308	(0.467)	26	0.245	0.171	0.260
1581-1590	48	0.141	0.182	0.140					(19	0.513	0.308)		20	0.310	0.216	(0.302)
1571-1580	44	0.143	0.182	0.137									(16	0.352	0.241)	
1561-1570	43	0.127	0.166	0.127												
1551-1560	41	0.112	0.152	0.119												
1541-1550	38	0.118	0.160	0.105												
1531-1540	38	0.085	0.127	0.097												
1521-1530	34	0.089	0.131	0.093												
1511-1520	29	0.105	0.148	0.098												
1501-1510	25	0.101	0.145	0.108												
1491-1500	22	0.118	0.161													

Table I.—*Average Annual Growth of Sequoias.*

Groups I to III are mature trees at Hume. Sections were cut from them in 1912. Groups marked *A* grew in damp places; those marked *B* in dry places. The trees of Group IV consist of young trees that grew at Dillonwood; those in group "*A*" are trees which began to grow before 1800 A. D.; those in group *B* are trees which began to grow before 1883. Group V consists of mature trees which were cut in 1911 at Camp No. 2, Hume. The number of trees and measurements is as follows: *I—A*, 22 trees, 23 measurements; *I—B*, 14 trees, 14 measurements; *II—A*, 25 trees, 31 measurements; *II—B*, 18 trees, 18 measurements; *III—A*, 22 trees, 25 measurements; IV—*a*, 5 trees, 8 measurements; IV—*b*, 19 trees, 46 measurements; V—*A*, 11 trees, 18 measurements. (See figures 42, 43, 44, and 48.)

Date.	Group I.		Group II.		Group III.	Group IV.		Group V.	Mean of Groups I-III.		Differential growth derived from weighted means.	Mean growth of groups I, II, III, V. Weighted.*
	A.	*B.*	*A*	*B.*	*A.*	*a.*	*b.*	*A.*	Weighted.	Un-weighted.*		
1910	2.92	3.14	1.64	1.72	1.21	1.45	4.05	1.41	3.29	2.01	−0.29	2.82
1909	2.95	3.38	1.91	1.88	1.28	1.30	4.05	1.37	3.58	2.16	−0.80	3.03
1908	3.09	3.81	1.74	2.03	1.34	1.31	4.12	1.38	2.66	2.24	+0.44	3.09
1907	2.70	3.29	1.51	1.84	1.17	1.51	3.95	1.39	3.22	1.95	+0.22	2.76
1906	2.56	2.79	1.42	1.54	1.21	1.45	3.20	1.38	3.00	1.80	−0.27	2.60
1905	2.91	3.36	1.48	1.88	1.18	1.38	3.05	1.35	3.27	2.05	−0.36	2.70
1904	2.94	3.70	1.60	1.79	1.20	1.35	3.73	1.18	3.63	2.08	+0.43	3.02
1903	2.83	3.50	1.44	1.70	1.19	1.68	4.63	1.41	3.20	1.96	−0.20	2.75
1902	3.20	3.76	1.43	1.92	1.23	1.40	4.08	1.40	3.40	2.12	+0.12	2.90
1901	3.40	3.53	1.35	1.83	1.17	1.38	4.59	1.30	3.28	2.07	+0.20	2.79
1900	3.03	3.25	1.28	1.63	1.05	1.41	4.72	1.23	2.99	1.89	−0.07	2.55
1899	2.94	3.31	1.23	1.73	1.16	1.39	4.34	1.26	3.06	1.91	−0.50	2.61
1898	3.38	3.93	1.57	1.98	1.25	1.29	4.32	1.22	3.56	2.24	−0.40	2.98
1897	4.58	4.51	1.76	1.90	1.28	1.36	4.64	1.44	3.96	2.60	−0.34	3.33
1896	4.63	4.78	2.00	1.93	1.47	1.35	3.90	1.68	4.30	2.76	±0.00	3.60
1895	4.37	4.93	2.00	1.87	1.54	1.53	4.23	1.55	4.30	2.74	+0.49	3.61
1894	3.82	4.31	1.76	2.05	1.22	1.65	4.35	1.62	3.81	2.44	+0.45	3.26
1893	3.67	3.68	1.63	1.54	1.06	1.36	4.44	1.48	3.36	2.17	−0.07	2.88
1892	3.52	3.71	1.54	1.74	1.14	1.39	4.32	1.35	3.43	2.20	−0.08	2.91
1891	3.52	4.23	1.50	1.98	1.12	1.05	4.35	1.34	3.51	2.25	+0.25	2.97
1890	3.56	3.43	1.47	1.72	1.06	1.26	4.46	1.48	3.26	2.10	−0.23	2.82
1889	3.54	4.40	1.62	1.80	1.19	1.29	3.60	1.23	3.59	2.30	+0.16	3.00
1888	3.47	4.06	1.58	1.68	1.14	1.41	3.98	1.34	3.43	2.18	−0.29	2.91
1887	4.07	4.20	1.72	1.79	1.20	1.30	3.73	1.20	3.72	2.35	−0.65	3.09
1886	4.57	5.55	2.01	2.26	1.30	1.36	3.52	1.24	4.37	2.72	+0.41	3.54
1885	4.32	5.05	1.68	2.09	1.17	1.58	3.70	1.33	3.96	2.48	+0.31	3.30
1884	4.11	4.08	1.63	1.82	1.15	1.19	3.64	1.26	3.65	2.18	+0.27	3.05
1883	3.58	4.01	1.56	1.38	1.16	1.35	3.50	1.15	3.38	2.14	−0.32	3.81
1882	3.64	4.23	1.72	2.21	1.17	1.34	3.75	1.32	3.70	2.27	+0.64	3.11
1881	3.36	3.35	1.41	1.82	0.98	1.65	2.87	1.51	3.06	1.74	−0.06	2.72
1880	2.66	3.41	1.44	1.82	1.02	1.11	3.42	1.20	3.12	1.80	+0.04	2.62
1879	2.85	3.86	1.37	1.99	0.95	(1.53)	....	1.42	3.08	1.87	+0.14	2.69
1878	2.73	3.02	1.36	1.77	0.93	(1.38)	....	1.52	2.94	1.72	−0.18	2.63
1877	2.58	3.36	1.46	1.78	1.02	....	....	1.51	3.12	1.77	−0.74	2.74
1876	2.76	3.22	1.84	2.33	1.18	....	....	1.42	3.86	2.04	+0.60	3.26
1875	2.55	2.93	1.54	1.85	1.06	....	....	1.58	3.26	1.77	−0.30	2.87
1874	2.60	3.15	1.80	1.97	1.06	....	....	1.56	3.56	1.91	+0.30	3.07
1873	2.35	2.82	1.55	1.79	1.08	....	....	1.01	3.26	1.69	+0.10	2.88
1872	2.44	3.16	1.63	1.59	1.00	....	....	1.43	3.16	1.70	−0.33	2.74
1871	2.52	3.32	1.75	1.83	1.12	....	....	1.53	3.49	1.85	−0.48	3.02
1870	3.07	3.40	2.06	2.07	1.22	....	....	1.52	3.97	2.12	+0.15	3.35
1869	3.07	4.28	1.80	2.27	1.20	....	....	1.64	3.82	2.12	+0.25	3.29
1868	3.68	4.37	1.76	1.96	1.12	....	....	1.54	3.57	2.03	+0.41	3.08
1867	2.71	3.39	1.58	1.75	0.97	....	....	1.58	3.16	1.75	−0.11	2.80
1866	2.95	3.11	1.67	1.82	0.98	....	....	1.61	3.27	1.79	+0.09	2.90
1865	2.36	3.24	1.56	1.89	0.94	....	....	1.67	3.18	1.66	−0.36	2.85
1864	....	....	1.91	1.99	0.98	....	....	1.72	3.54	1.87	+0.16	3.12
1863	....	....	1.68	1.90	1.04	....	....	1.55	3.38	1.87	−0.13	2.95
1862	....	....	1.81	1.88	1.07	....	....	1.72	3.51	1.86	+0.31	3.10
1861	....	....	1.64	1.73	0.96	....	....	1.81	3.20	1.60	+0.25	2.92
1860	....	....	1.49	1.55	0.93	....	....	1.67	2.95	1.72	−0.06	2.68
1859	....	....	1.49	1.74	0.90	....	....	1.78	3.01	1.46	−0.33	2.76
1858	....	....	1.75	2.01	0.88	....	....	1.82	3.34	1.63	+0.10	3.01
1857	....	....	1.68	1.94	0.87	....	....	2.00	3.24	1.63	−0.15	3.01
1856	....	....	1.84	2.04	0.85	....	....	2.11	3.39	1.68	−0.11	3.15
1855	....	....	1.91	2.04	0.90	....	....	1.71	3.50	1.70	−0.11	3.09
1854	....	....	1.94	2.28	0.88	....	....	1.86	3.63	1.73	−0.13	3.24
1853	....	....	2.07	2.12	0.89	....	....	1.62	3.66	1.78	−0.03	3.17
1852	....	....	1.97	1.95	0.94	....	....	1.65	3.55	1.63	+0.11	3.11
1851	....	....	2.07	2.03	1.08	....	....	1.70	3.79	1.75	−0.24	3.29
1850	....	....	2.11	2.09	1.06	....	....	1.76	3.86	1.80	−0.07	3.37
1849	....	....	1.98	2.03	0.99	....	....	2.07	3.33	1.67	+0.53	3.39
1848	....	....	1.89	1.88	0.98	....	....	1.61	3.29	1.58	+0.04	2.99
1847	....	....	1.63	1.74	0.88	....	....	1.81	2.95	....	....	2.99
1846	....	....	1.65	1.67	0.94	....	....	1.62	3.16	....	....	2.94
1845	....	....	1.38	1.71	0.92	....	....	1.58	3.09	....	....	2.87
1844	....	....	1.36	1.76	0.93	....	....	1.39	3.12	....	....	2.72
1843	....	....	1.33	1.79	1.03	....	....	1.58	3.45	....	....	3.04
1842	....	....	1.70	1.69	1.04	....	....	1.51	3.49	....	....	3.00
1841	....	....	1.73	1.62	1.12	....	....	1.42	3.76	....	....	3.07

* The unweighted means are obtained by adding all the totals and dividing by the number of measurements. In the weighted means the different groups have been given such a weight that the value of a single measurement is the same, no matter whether the average growth of the group is great or small.

Date.	Group II. A.	Group II. B.	Group III. A.	Group V. A.	Mean of Groups 1–III. Weighted.	Mean growth of groups 1, 2, 3, 5. Weighted.*	Group V. Date.	Group V. A.	Group V. Date.	Group V. A.	Group V. Date.	Group V. A.	Group V. Date.	Group V. A.
1840	1.80	1.72	1.20	1.41	4.03	3.19	1760	1.51	1680	1.86	1600	1.40	1520	2.02
1839	1.68	1.61	1.22	1.27	4.09	3.10	1759	1.39	1679	1.83	1599	1.59	1519	2.08
1838	1.69	1.67	1.14	1.49	3.83	3.16	1758	1.60	1378	1.85	1598	1.53	1518	1.91
1837	1.56	1.68	1.15	1.55	3.86	3.22	1757	1.49	1677	1.87	1597	1.62	1517	1.94
1836	1.51	1.65	1.20	1.40	4.03	3.25	1756	1.45	1676	1.89	1696	1.74	1516	2.25
1835	1.65	2.06	1.31	1.58	4.40	3.52	1755	1.92	1675	1.88	1595	1.72	1515	1.94
1834	1.87	2.44	1.26	1.41	4.23	3.20	1754	1.67	1674	1.82	1594	1.60	1514	1.65
1833	1.91	2.24	1.20	1.40	4.03	3.18	1753	1.65	1673	1.73	1593	1.79	1513	1.67
1832	1.57	2.36	1.01	1.58	3.39	3.01	1752	1.56	1672	1.76	1592	1.74	1512	1.71
1831	1.65	1.57	1.05	1.67	3.52	3.14	1751	1.70	1671	1.48	1591	1.53	1511	1.83
1830	1.65	1.67	0.88	1.42	2.95	2.65	1750	1.56	1670	1.67	1590	1.57	1510	2.16
1829	1.58	1.76	0.90	1.37	3.02	2.34	1749	1.63	1669	1.83	1589	1.67	1509	1.98
1828	1.52	1.73	1.00	1.65	3.36	3.05	1748	1.71	1668	1.90	1588	1.92	1508	1.98
1827	1.40	....	0.88	1.27	*2.95	*2.53	1747	1.62	1667	1.75	1587	1.75	1507	1.87
1826	1.53	....	0.96	1.50	3.22	2.86	1746	1.59	1666	1.73	1586	1.63	1506	2.27
1825	1.42	....	0.89	1.60	2.98	2.82	1745	1.57	1665	1.91	1585	1.57	1505	2.29
1824	1.52	....	0.89	1.51	2.98	2.74	1744	1.60	1664	1.82	1584	1.19	1504	2.37
1823	1.34	....	0.94	1.51	3.16	2.84	1743	1.51	1663	2.01	1583	1.52	....	....
1822	1.55	....	1.06	1.65	3.55	3.14	1742	1.54	1662	1.77	1582	1.49	....	....
1821	2.09	....	0.90	1.81	3.02	3.03	1741	1.43	1661	1.93	1581	1.59	....	....
1820	1.97	....	0.89	1.54	2.98	2.77	1740	1.49	1660	1.79	1580	1.54	....	....
1819	1.91	....	0.94	1.59	3.16	2.90	1739	1.54	1659	1.54	1579	1.48	....	....
1818	1.73	....	0.97	1.59	3.26	2.94	1738	1.72	1658	1.72	1578	1.59	....	....
1817	....	....	1.03	1.56	3.45	3.02	1737	1.51	1657	1.58	1577	1.65	....	....
1816	....	....	1.19	1.69	3.99	3.40	1736	1.32	1656	1.62	1576	1.59	....	....
1815	....	....	1.21	1.57	4.06	3.33	1735	1.53	1655	1.57	1575	1.52	....	....
1814	....	....	1.20	1.63	4.33	3.51	1734	1.81	1654	1.65	1574	1.75	....	....
1813	....	....	1.22	1.63	4.09	3.26	1733	1.74	1653	1.67	1573	1.97	....	....
1812	....	....	1.38	1.72	4.63	3.74	1732	1.84	1652	1.77	1572	2.06	....	....
1811	....	....	1.35	1.81	4.09	3.59	1731	1.81	1651	1.81	1571	1.78	....	....
1810	....	....	1.24	1.61	3.57	3.17	1730	1.53	1650	1.82	1570	1.86	....	....
1809	....	....	1.21	1.80	3.31	3.29	1729	1.66	1649	1.66	1569	1.81	....	....
1808	....	....	....	1.76	2.74	3.02	1728	1.94	1648	1.87	1568	2.05	....	....
1807	....	....	....	1.74	2.77	3.01	1727	1.86	1647	1.68	1567	1.78	....	....
1806	....	....	....	1.63	2.82	2.91	1726	2.28	1646	1.74	1566	1.88	....	....
1805	....	....	....	1.78	3.11	3.18	1725	1.73	1645	1.68	1565	1.94	....	....
1804	....	....	....	1.80	3.11	3.22	1724	1.44	1644	1.88	1564	2.12	....	....
1803	....	....	....	1.91	3.97	3.67	1723	1.47	1643	1.90	1563	2.14	....	....
1802	....	....	....	1.95	3.40	3.49	1722	1.57	1642	1.70	1562	2.01	....	....
1801	....	....	....	1.85	2.91	3.20	1721	1.64	1641	2.02	1561	1.96	....	....
1800	....	....	....	1.86	2.65	3.11	1720	1.55	1640	1.87	1560	2.02	....	....
1799	....	....	....	1.60	2.65	2.81	1719	1.58	1639	1.90	1559	1.97	....	....
1798	....	....	....	1.67	2.48	2.82	1718	1.66	1638	1.72	1558	1.83	....	....
1797	....	....	....	1.68	2.33	2.78	1717	1.67	1637	1.65	1557	2.05	....	....
1796	....	....	....	1.53	2.19	2.56	1716	1.96	1636	1.72	1556	1.69	....	....
1795	....	....	....	1.50	3.30	2.94	1715	1.79	1635	1.90	1555	1.92	....	....
1794	....	....	....	1.51	4.29	3.36	1714	1.74	1634	1.94	1554	1.96	....	....
1793	....	....	....	1.71	3.39	3.22	1713	1.65	1633	1.92	1553	1.82	....	....
1792	....	....	....	1.88	3.23	3.36	1712	1.85	1632	1.89	1552	1.53	....	....
1791	....	....	....	1.78	3.23	3.23	1711	1.91	1631	1.80	1551	1.67	....	....
1790	....	....	....	1.94	2.97	3.32	1710	1.96	1630	1.84	1550	1.68	....	....
1789	....	....	....	1.82	3.36	2.96	1709	1.80	1629	1.23	1549	1.49	....	....
1788	....	....	....	1.90	3.00	3.29	1708	1.94	1628	2.04	1548	1.43	....	....
1787	....	....	....	1.77	2.43	2.94	1707	2.00	1627	1.98	1547	1.35	....	....
1786	....	....	....	1.66	2.68	2.90	1706	2.13	1626	1.87	1546	1.55	....	....
1785	....	....	....	1.69	2.33	2.79	1705	2.01	1625	1.98	1545	1.83	....	....
1784	....	....	....	1.67	2.25	2.74	1704	1.95	1624	2.08	1544	1.84	....	....
1783	....	....	....	1.47	2.62	2.66	1703	2.01	1623	2.09	1543	1.83	....	....
1782	....	....	....	1.41	2.91	2.70	1702	1.78	1622	2.16	1542	2.54	....	....
1781	....	....	....	1.38	3.08	2.73	1701	1.57	1621	2.29	1541	2.18	....	....
1780	....	....	....	1.70	2.77	2.97	1700	1.61	1620	2.38	1540	2.14	....	....
1779	....	....	....	1.47	2.97	2.78	1699	1.62	1619	2.66	1539	2.18	....	....
1778	....	....	....	1.29	2.97	2.58	1698	1.68	1618	2.30	1538	2.18	....	....
1777	....	....	....	1.47	4.24	3.26	1697	1.68	1617	2.49	1537	1.97	....	....
1776	....	....	....	1.53	3.86	3.18	1696	1.73	1616	2.47	1536	2.14	....	....
1775	....	....	....	1.56	3.55	3.11	1695	1.71	1615	2.62	1535	2.16	....	....
1774	....	....	....	1.55	3.26	2.99	1694	1.78	1614	2.60	1534	1.85	....	....
1773	....	....	....	1.41	3.26	2.82	1693	1.57	1613	2.52	1533	1.97	....	....
1772	....	....	....	1.43	3.00	2.75	1692	1.74	1612	2.68	1532	2.22	....	....
1771	....	....	....	1.45	3.26	2.87	1691	1.67	1611	2.66	1531	2.01	....	....
1770	....	....	....	1.31	3.57	2.84	1690	1.79	1610	2.15	1530	2.19	....	....
1769	....	....	....	1.30	3.60	2.84	1689	1.80	1609	2.31	1529	2.10	....	....
1768	....	....	....	1.27	3.72	2.85	1688	1.80	1608	2.41	1528	2.08	....	....
1767	....	....	....	1.43	3.46	2.93	1687	1.95	1607	2.07	1527	1.95	....	....
1766	....	....	....	1.37	*3.08	*2.72	1686	1.71	1606	1.80	1526	1.85	....	....
1765	....	....	....	1.33	....	....	1685	2.00	1605	1.81	1525	1.94	....	....
1764	....	....	....	1.44	....	....	1684	1.78	1604	2.09	1524	1.93	....	....
1763	....	....	....	1.33	....	....	1683	2.19	1603	1.72	1523	1.99	....	....
1762	....	....	....	1.65	....	....	1682	2.03	1602	1.83	1522	1.96	....	....
1761	....	....	....	1.44	....	....	1681	2.00	1601	1.54	1521	1.71	....	....

* The portions of these columns between the stars are based not only on the figures here given in the columns to the left, but also on portions of groups II and III, which are here omitted because they are based on a number of trees smaller than the number indicated at the top of the first part of this table.

The minus sign indicates that the tree made no ring in this particular year. A plus sign indicates an extra ring. D after the date signifies that in the straight-away count this ring was noticed, but was considered a double, and hence was reckoned with one of the adjacent years. The brackets mean that the ring was actually measured but still considered a double belonging with its neighbor.

[Table compiled by A. E. Douglass.]

No. of section.	Age in years.	No. of years for which identification is complete.	Year supposed to be 1700 A. D. in first count.	Errors in last 100 years.	Errors in next to last 100 years.	Errors in portions dating back more than 200 years.
VII	212	200	1705	−1892, −[1828], −[1821], −[1813]	−[1747D]	....
VIII	333	322	1701	−[1821]	....	....
IX	409	406	1714	−1902, −1893, −1892, −1891, −1890, −[1885], −1878D, −1821, −1813	−[1781], −1772, −1752, −[1747], −[1734]	−[1669], −[1631], −[1584], −[1541], −[1531]
X	328	322	1703	−1821	−[1751], −[1734[	....
XI	326	320	1718	15 errors between 1910 and 1870 −1863, −1840, −1813	....	−1608, −[1599]
XII	528	520	1702	−[1821]	−1751D	−[1653], +1652½, +1650½, −1640D, −1584, −1583, +1553½, +1552½, −1541, −1531, −[1499], −[1463], −1462, −[1433], −1420D, −1418D, −1412
XIII	520	518	1710	−[1903], −[1846], −[1844], −1841D, −1839, −1821, −1819, −1817, −1813	−1752	−1659, −1653, −1632, −1600, −1584, −1583, −[1579], −1565*, −1564*, −1531, −[1521], −1481D, −[1462]
XIV	331	330	1706	−1873, −[1846], −[1821], −[1819]	−[1781], −1776D	+1634½, −1584, −1583
XV	363	350	1703	+1907, −1903D, −1893, −1892, −1891, −1890, −1882D, −1879D, +1833½, −1821	−[1751], −1734D	....
XVI	378	377	1706	+1907, −1846, −1844, −1821, −1813	−1751, −[1747], −[1734]	−1669, −[1653], −1631D
XVII	413	407	1707	−[1903], −[1901], −[1821], −1813	+1802½, −1788, −[1772], −1751, −[1734]	−[1669], −[1653], −[1631]
XVIII	217	212	1700	−1817	+1773½	....
XIX	243	237	1700	....	....	....
XX	300	....	1730	−1903D, −1901D, −1896, −1895, −1894, −1893, −1892, −1891, −1890, −1848, −1844, −1841, −1838, −1834, −1821, −1819, −1817, −1816, −1813D	−1807, −1801, −[1788], −1781, −1778, −1770, −1760, −1758, −1751, −[1747], −1734	....
XXI	267	260	1702	−1821	−1751	+1649½
XXII	345	344	1705	−1846D, −[1821], −[1819]	−[1751], −[1734]	−1583D
XXIII	410	408	1717	−1904, −1903, −1902, −1901, −1899, −1896, −1895, −1894, −1893, −1892, −1891, −1890, −1879D, −1821	−[1781], −1751, −[1747], −1734	−1669, −1632, −1599, −1584, −1583, +1566½, −[1541]
XXIV	349	346	1710	−1846, −1841, −1821, −1819, −1814, −1813D	−1772D, −1756, −1751, −1734	....
XXV	350	350	1711	−[1901], −1895, −1879, −1878D, −[1841], −1821, −1814, −1813	+1784½, −1772D, −1751, −[1747], −1734	−[1669], −[1653], −[1631], −[1584]
Average...	348					

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